An Analysis of Leakage Parameters of Individual Leaks on a Pressure Pipeline through the Development and Application of a Standard Procedure

DEPARTMENT OF CIVIL ENGINEERING

Masters Dissertation

By: Rahil Malde (MLDRAH001)

Supervisor: Professor J.E. van Zyl

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ABSTRACT

Water is a vital and scarce resource. Providing a sustainable and efficient means of transporting water is essential to the wellbeing of humankind. Most water distribution systems worldwide are ageing and deteriorating, as a result, leakage is a common problem. Modern water distribution systems use a variety of methods to minimise leakage, one of them is pressure management. However, the relationship between leakage and pressure is a complex one.

The goals of this study were to develop a standard experimental procedure to determine the leakage parameters of a pipe with an individual leak, and to test a series of pipes using the newly developed procedure to determine their leakage parameters. There have been numerous experimental investigations into the leakage parameters; however, these investigations have variation in their methodologies. Therefore, developing a standard procedure will provide a consistent method for the accurate determination of the leakage parameters.

Leakage parameters are important as they help to improve the understanding of the relationship between leakage and pressure. They are also important for use in the two main equations used to relate leakage and pressure, i.e. the N1 equation and the FAVAD equation. The determination of a variety of leakage parameters will help to determine whether both equations explain the behaviour of a variety of pipe samples, and which equation is better suited for use in leakage prediction.

The leakage parameters were determined by initially developing a standard experimental setup and data analysis method. This experimental procedure was put through a few verification tests before a series of pipes with artificially induced leaks was tested.

Round holes were found to be the most stable leak type, whereas, circumferential, longitudinal and spiral leaks all experienced large amounts of deformation. The leakage exponents ranged from -2.3 to 1.1, showing a wide range of change in the leak area. Both the N1 and FAVAD equations were successful in predicting the behaviour of the different pipe samples.

This investigation showed that the leakage parameters can have a large range of variation depending on the pipe material and leak type. Having an accurate, standard experimental procedure to determine leakage parameters is essential to better understand the relationship between leakage and pressure. This in turn will improve the pressure management systems and minimise leakage, with the overall aim of providing a sustainable and efficient means of transporting water and protecting a vital resource.

ACKNOWLEDGMENTS

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LIST OF ABBREVIATIONS

AC - Asbestos Cement

C - Leakage Coefficient

C_d - Coefficient of Discharge

CI - Cast Iron

DWA - Department of Water Affairs

FAVAD - Fixed and Variable Area Discharge

FEA - Finite Element Analysis

HDPE - High-Density Polyethylene

m - Head-area Slope

N1 - Leakage Exponent

NRW - Non-Revenue Water

OD - Outer Diameter

R^2 - Coefficient of Correlation

Re - Reynolds number

SANS - South African National Standards

SASOL - South Africa Synthetic Oil Liquid

SSE - Sum of Squared Errors

T_w - Wall thickness

mPVC - Modified Polyvinyl Chloride

uPVC - Unplasticised Polyvinyl Chloride

VJ - Viking Johnson

WDS - Water Distribution Systems

VSD - Variable Speed Drive

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1. Introduction

1.1 Background to the Study

Water is the most vital resource the earth has to offer. For centuries, humankind has adopted methods to acquire and provide water for consumption. Urbanisation has led to densely populated areas that have a high demand for water. Today the most efficient means of providing water to an urban area is through the use of a Water Distribution System (WDS). A water distribution system consists of a pipe network that transports water from a storage unit to the consumers.

Water is also a scarce resource and therefore providing an efficient and sustainable means of transporting water is crucial to the existence of humankind. Most water distribution systems around the world were implemented more than a hundred years ago and a lack of maintenance coupled with an increase in consumption has led to the deterioration of these water distribution systems.

Greyvenstein and van Zyl (2007) state that water losses have a negative impact on the level of service of the water distribution system whilst incurring costs to the water suppliers and increasing the environmental impact of water extractions. Water losses consist of various components including leakage, illegitimate use, unmetered use and under-registration of water. The World Health Organisation (WHO) (2001) explains that leakage is responsible for most of the water losses which are sometimes more than 70% of the systems total input volume.

Pressure management is used as a tool to control leakage (Nicolini & Zovatto, 2009). This entails adjusting the network's internal water pressure to minimise leakage while still providing the consumer with a suitable water pressure.

The relationship between pressure and leakage is a complex one. This complexity is brought about by a variety of factors, including leakage parameters, pipe material properties and leak geometry that affect leakage behaviour.

There are two common equations that are used to relate pressure and leakage. The first equation is called the N1 equation and is a generalisation of the orifice equation. This is done by making the exponent of the orifice equation a variable function. The second equation is known as the Fixed and Variable Area Discharge (FAVAD) equation which was developed in the 1990's. This equation is based on the assumption that the leak area expands linearly with pressure. Both these equations will be explained in detail in the Literature Review chapter.

A variety of investigations have been carried out to estimate the leakage parameters as a better understanding of these parameters will help us predict the behaviour of leaks. There have been both experimental and modelling investigations into the determination of parameters. However, the different experimental investigations have used different experimental procedures and there is no standard procedure to determine these parameters experimentally.

1.2 Problem Statement

A standard experimental procedure is required to efficiently test a pipe with an individual leak and determine its respective leakage parameters. The experimental procedure needs to be robust and the data analysis method has to provide accurate results. A further investigation is required on the leakage parameters as well as the N1 and FAVAD equations to develop a better understanding of the relationship between pressure and leakage.

1.3 Aims and Objectives

This investigation has two aims. The first aim is to develop a standard experimental procedure to determine the leakage parameters of a pipe with an individual leak. The second aim is to test a series of pipes using the developed standard procedure and determine their leakage parameters.

Each of the above aims has their own set of objectives, namely:

1.) To develop a standard experimental procedure to determine the leakage parameters of a pipe with an individual leak, meeting the following requirements:

   - the experimental setup must be able to contain a pipe sample under high internal water pressure
   - the setup should be able to be assembled easily and efficiently
   - a data analysis method must be developed to efficiently analyse all the collected data
   - the experimental setup and data analysis method must be verified.

2.) To test a series of pipes using the developed standard procedure and determine their leakage parameters, taking the following steps:

   - select a range of pipe materials to be used for testing
   - artificially induce a variety of leak types into the pipe samples
   - determine the leakage parameters of the pipe samples using the standard experimental procedure
   - evaluate the N1 and FAVAD parameters in the context of the latest research and development in the field.

1.4 Limitations and Scope of the Investigation

The experimental setup used in this investigation will only test pipe samples with an outer diameter of 110mm and a length 800mm. The restriction on 110mm is due to the Viking Johnson (VJ) couplings which can only fit a sample of that diameter. However, if for further investigation different pipe diameters are required, the methodology section of this report will give a detailed description of the design process which will allow for a simple reconstruction of the setup with any pipe diameter size.

The restriction on the 800mm section was a compromise between the amount of available pipe material length and the amount of pipe samples needed. The experimental setup is adjustable by length which allows a range of pipe lengths to be tested. The maximum and minimum lengths that can be tested are 1800mm and 400mm respectively.

The material selected for testing will be limited to mPVC, uPVC, HDPE and steel. mPVC, uPVC and HDPE are common pipe materials used in modern water distribution systems. Steel is also a common pipe material used but mainly in bulk systems, high pressure systems and fittings.

Failed water pipes from Cape Town's water distribution systems were acquired from the City of Cape Town (CoCT) municipality; however, the samples were either too large or failed beyond the point of testing. Therefore only artificially induced leaks were used in the form of round holes, circumferential cracks, longitudinal cracks and spiral cracks. The round holes were limited to a size of 12mm diameter. The cracks lengths used are 50mm, 75mm and 100mm but unfortunately due to the lack of pipe samples not each crack length could be induced in each material. This means that while some crack types, such as the spiral 50mm, are present for all pipe materials, some crack types, such as the circumferential 50mm, is only present in one pipe material.

Leakage parameters are not used consistently around the world and therefore specific denotations of the leakage parameters are important for all experimental investigations. This investigation will be focused on determining the Leakage Coefficient (C), the Coefficient of Discharge (C_d), the Leakage Exponent (N1), the initial leak area (A_0) and the Head-area Slope (m).

The statistical analysis will be kept simple and basic with the use of two statistical tools, namely the Coefficient of Correlation (R^2) and the Sum of Squared Errors (SSE). These will be used to draw comparisons between the experimental data and the N1 and FAVAD equations only.

1.5 Layout for the Investigation

This investigation begins in chapter 2 with a review of literature on the relationship between pressure and leakage. The focus will be on pipe material behaviour, leak hydraulics and previous experimental methods used to determine any of the leakage parameters.

Chapter 3 explains the methodology, describing the development of a suitable experimental procedure to determine the leakage parameters. This entails designing an experimental setup and data analysis method. The experimental procedure then undergoes a series of verification tests to ensure the efficiency and consistency of the collected experimental data. Adjustments were made to improve the quality of the results before presenting a list of pipe samples for testing.

Chapter 4 presents the results on each of the leak samples tested alongside a short discussion of the findings. A discussion on omitted values is followed by an overall discussion of the results.

Finally Chapter 5 discusses the conclusions drawn from the findings of this investigation, followed by recommendations for improvements. Lastly, the appendices present the relevant information used in this investigation including experimental results, flow meter specifications and the code for a data analysis programme developed.

2. Literature Review

This chapter analyses relevant literature in order to develop a full understanding of the problem under investigation. The exploration will begin with an overview of the problem as presented in the literature. This will be followed by an in-depth study of the relationship between leakage and pressure as well as its influencing factors. The focus will be on the behaviour of leaks, and a discussion of pipe materials, leak hydraulics and failure modes will be presented. Lastly, this chapter will briefly discuss soil hydraulics and how water travels through the ground.

2.1 General Overview

Potable water is today considered a scarce resource. South Africa is considered to be a water scarce country. A sustainable water supply is vital for the well-being of humankind. Large costs are incurred for the provision of clean, safe potable water due to construction and maintenance of storage facilities, pumping stations, dams, distribution pipe lines and other services. For this reason it is important that water losses from systems are well understood in order to reduce and eventually eliminate water losses.

The increase in water losses from water distribution systems is a great concern for municipalities in South Africa. It reduces the efficiency of water distribution systems and results in a capital loss as potable water has a monetary value. Water distribution systems are designed for peak consumption and therefore undergo long periods of excessive pressures when consumption is low (Nicolini & Zovatto, 2009).

In 2012, McKenzie et al (2012) gathered data, with the assistance of the Department of Water Affairs (DWA) from 132 out of 237 South African municipalities, which represented 75% of the total volume of South Africa’s municipal water supply. The results showed that 36.8% of the total system input volume has been classified as Non-Revenue Water (NRW). Furthermore, approximately 70% of this NRW comprises of physical leakage. Table 2.1 shows the National Water Balances (2009/10) breakdown for Revenue Water and Non-Revenue Water.

Real and physical losses are divided into two types of leakage, pipe bursts and background leakage. To distinguish between pipe bursts and background leakage, each been defined as follows: pipe bursts are considered to be large individual leaks that break the surface of the ground or are found by active leakage control initiatives; background leakage is considered to be a collection of small leaks which are difficult to detect without excavation (Clayton & van Zyl, 2007).

Table 2.1: National Water Balance (2009/10) in South Africa (McKenzie et al., 2012).

<table>
<tr><td rowspan="4">System Input Volume
(100%)</td><td rowspan="2">Authorised Consumption
(68.2%)</td><td>Billed Authorised
(63.2%)</td><td>Revenue Water
(63.2%)</td></tr>
<tr><td>Unbilled Authorised **(5.0%)**</td><td rowspan="3">Non-Revenue Water
(36.8%)</td></tr>
<tr><td rowspan="2">Water Losses
(31.8%)</td><td>Commercial Losses **(6.4%)**</td></tr>
<tr><td>Real or Physical Losses
(25.4%)</td></tr>
</table>

Various factors can affect leakage but out of all the existing factors, only pressure can be controlled once the pipes have been laid. In a well-run water distribution system, pressure management is used to minimise both background leakage and pipe bursts. The aim of pressure management is to minimise as far as possible any excessive pressures in a system while ensuring that sufficient pressure is provided to the consumer (Vairavamoorthy & Lumbers, 1998).

There are a variety of methods that have been developed to optimise pressure management. Most of these methods are based on optimal valve control as shown by Vairavamoorthy and Lumbers (1998), Araujo et al. (2006) and Nicolini and Zovatto (2009). All these investigations explain how minimising excessive pressures in a water distribution system will minimise leakage. However each of the investigations uses its own methods for reducing leakage. Vairavamoorthy and Lumbers (1998) focus on the inclusion of flow control valves. Araujo et al. (2006) discuss the importance of quantification, location and adjustment of control valves. Nicolini and Zovatto (2009) discuss the introduction of more Pressure Reducing Valves into water networks. Although researchers have different ideas on how to minimise leakage, there is an agreement amongst researchers that the relationship between leakage and pressure is a complex one with many factors to be considered.

2.2 The Relationship between Leakage and Pressure

This section will discuss the relationship between leakage and pressure. There are many factors that influence the relationship between pressure and leakage; three of them are: expansion of leak area due to pressure, leak hydraulics and soil hydraulics. Each of these factors will be discussed, but the focus will be kept on the expansion of leak areas for experimental investigation. Water demand and the effect of combined leaks are also two factors that affect pressure and leakage but due to the nature of this investigation they will not be discussed.

2.2.1 Expansion of Leak Area Due to Pressure

This section focuses on different factors and considerations concerned with the expansion of leak areas with pressure.

2.2.1.1 The Analytical Approach

Conventionally, the relationship between pressure and leakage has been described by the orifice equation (Equation 1). Here Q is the leak flow, C_d is the coefficient of discharge, A is the leak area, g is the acceleration due to gravity and h is the pressure head. This equation describes the flow as insensitive to pressure (Clayton & van Zyl, 2007).

$$q = C_d A\sqrt{2gh} \tag{1}$$

Equation 1 is originally derived from an orifice in the bottom of a tank and describes the conversion from potential energy to kinetic energy. C_d is used to account for energy losses and the reduction of the jet diameter downstream of the orifice. If equation 1 is applied to the leak flow from a pipe then it can be written in a more general form as shown by equation 2, which is the power equation and will be referred to as the N1 equation:

$$Q_L = Ch^{N1} \tag{2}$$

Where Q_L is the flow through the leak, C is the leakage coefficient, h is the pressure head and N1 is the leakage exponent. The N1 value is a more important parameter than the C value because of its position as an exponent. Therefore is has a greater influence on the leak flow than the C value does (Clayton & van Zyl, 2007).

A number of field studies on systems with several leaks show that N1 ranges between 0.5 and 2.8 with a median of 1.15. There are also some studies that have shown leakage exponents less than 0.5 which relates to a decrease in the size of the leak area (Greyvenstein, 2004). The variation in N1 values show that leakage in water distribution systems is more sensitive to pressure than conventionally assumed (Clayton & van Zyl, 2007).

An example to demonstrate the importance of N1 is as follows: if the pressure at a leak is halved, then the reduction in leak flow for each respective N1 is shown in table 2.2 below.

Table 2.2: Reduction in leak flow with respect to leakage exponent (Clayton & van Zyl, 2007).

N1	0.5	1	2.5
Reduction in Leak flow (%)	29	50	82

Table 2.2 shows that the leakage exponent has a considerable effect on the leak flow. The large influence of N1 while estimating the potential impact of pressure management of leakage rates shows how important it is to develop a clear understanding of the behaviour of this mechanism.

2.2.1.2 Experimental Investigations

Various methods have been used in the past to determine leakage exponents. In 2007, Greyvenstein and van Zyl developed a setup to determine the leakage exponent of an individual leak while trying to replicate normal water distribution system conditions for the pipe. The setup consists of two removable end sections that are held in place by threaded steel rods and nuts. The failed pipe sample would be fitted in between the end sections and secured. One end section has a water inlet and the other section has a pressure transducer. Figure 2.1 shows a drawing of the setup used.

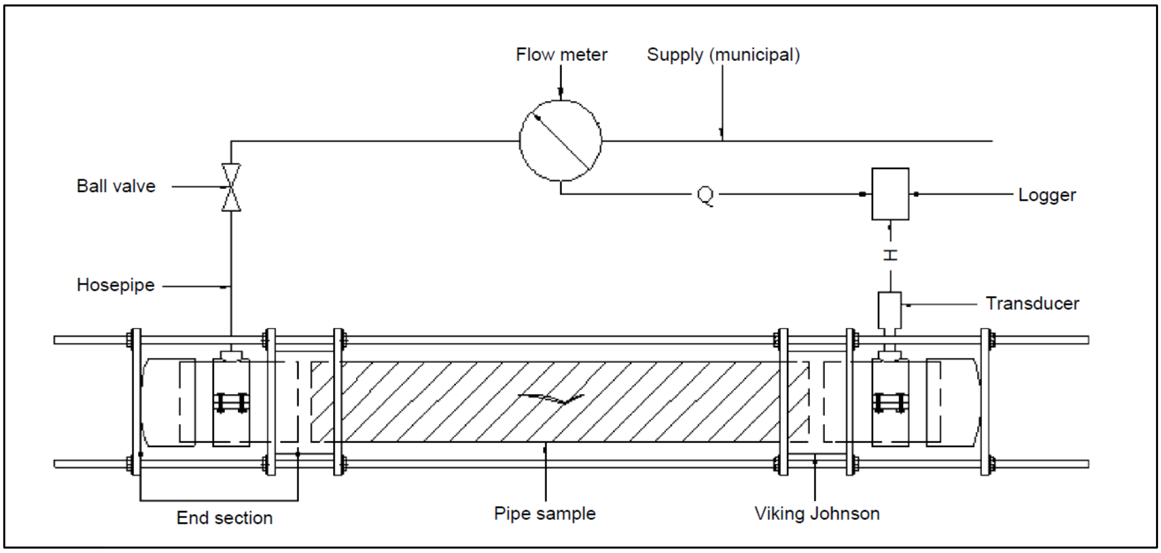

Figure 2.1: Drawing of setup used to determine leakage exponent of an individual leak (Greyvenstein & van Zyl, 2007).

The setup is connected to the municipal water supply network by a hose pipe which also has a combination turbine flow meter. A data logger is used to collect readings from the flow meter and pressure transducer. Initially, before testing, the setup needs to be filled with water and any air removed. The pressure in the system is controlled by a lever ball valve, which is increased at intervals of 30 seconds and then decreased at the same intervals to produce step up and step down sets of data points. Figure 2.2 shows a typical set of raw data taken from Greyvenstein (2004).

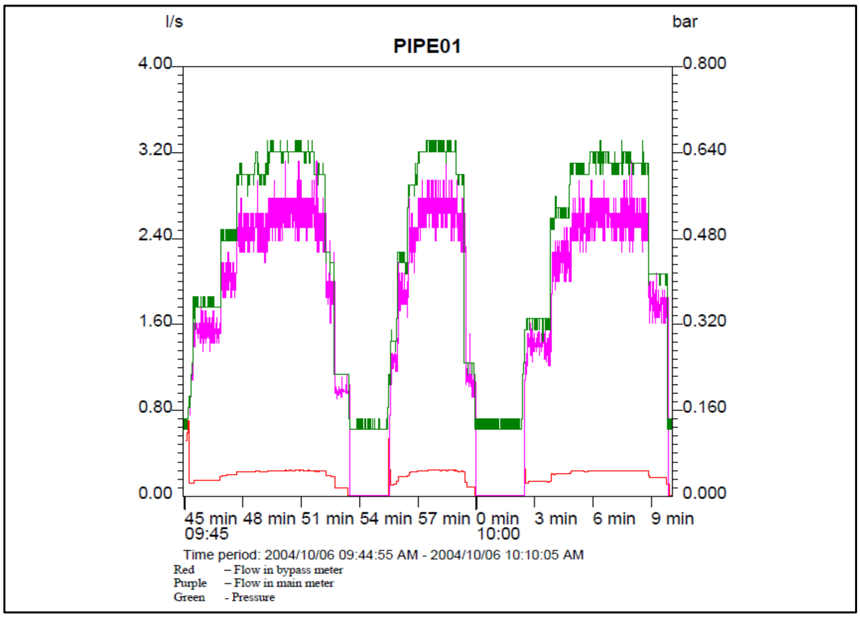

Figure 2.2: Typical set of raw data (Greyvenstein, 2004).

The short term fluctuations are caused by transients that exist in the municipal water supply line but are not considered to be a concern as they occur naturally in water distribution systems. To collect suitable data points, Greyvenstein (2004) had to identify relatively stable sections of the graph where he could take an average value over the ranges. These values were then plotted and analysed to determine the leakage exponents for each pipe sample.

Greyvenstein (2004) focused his experiments on 3 types of pipe materials (asbestos cement, uPVC and steel) as well as 3 types of leak openings (round holes, circumferential and longitudinal). The results can be seen in Table 2.3.

Table 2.3: Summary of results from Greyvenstein and van Zyl (2007).

Material	Sample	Pipe Source	Pipe Dimensions OD/T_w (mm)	Fracture Type	Fracture Dimensions (mm)	Leakage Exponent (N1)	Coefficient of determination (R^2)
AC	1	JWDS	100/12	Longitudinal into bell shaped	324 (longitudinal only)	0.91	0.99800
AC	2	JWDS	100/12	Longitudinal into bell shaped	298 (longitudinal only)	0.79	0.95800
AC	3	JWDS	100/12	Longitudinal into bell shaped	256 (longitudinal only)	1.04	0.98100
Steel	4	JWDS	115/3	2 Corrosion holes	Diameters 20 and 4	0.67	0.97800
Steel	5	JWDS	90/4	3 Corrosion holes (circular, rectangular and triangular)	20, 43 x 11 and 30 respectively	1.96	0.79800
Steel	6	JWDS	85/3	Corrosion cluster (more than 25 holes)	Ranging from 2 -10	2.30	0.92700
Steel	7	JWDS (No damage)	110/4	Artificially Induced (AI) drilled hole	12	0.518	0.99995
uPVC	8	New	110/3	AI Round hole	12	0.524	0.99986
uPVC	9	New	110/3	AI Circumferential	90 (1mm Width)	0.41	0.98900
uPVC	10	New	110/3	AI Circumferential	170 (1mm Width)	0.50	0.99500
uPVC	11	New	110/3	AI Circumferential	270 (1mm Width)	0.53	0.99800
uPVC	12	New	110/3	AI Longitudinal	50 (1mm Width)	1.51	0.95400
uPVC	13	New	110/3	AI Longitudinal	100 (1mm Width)	1.46	0.97400
uPVC	14	New	110/3	AI Longitudinal	150 (1mm Width)	1.85	0.87500

Sample 2 of the AC pipes has a lower exponent than expected; Greyvenstein (2004) explains that this could be due to the longitudinal crack being at a slight angle instead of longitudinal like in samples 1 and 3. This shows that the effect of a longitudinal crack at an angle would have a different behaviour that still needs to be verified.

From the results of the steel pipe samples, it is clear that corrosion damage weakens the area around the leak opening, causing the leakage exponent to increase considerably. The highest leakage exponents were found in steel pipes with corrosion damage, in particular corrosion clusters. This would be a more likely scenario in a water distribution system as corrosion damage is most common in steel pipes. Plastic pipes have been considered to have higher leakage exponents compared to steel due to their lower modulus of elasticity, however this is not always the case as shown in Greyvenstein's (2004) results.

The tests done by Greyvenstein (2004) had flows with Reynolds numbers greater than 5 000, indicating that turbulent flow had developed through the leak. For the Reynolds number calculations (refer to equation 23), V is the leak jet velocity and D is the leak diameter From the results of the Asbestos Cement (AC) pipes no direct relation could be found between crack length and leakage exponent. However, the uPVC (un-plasticised Polyvinyl Chloride) pipe samples showed a trend of increasing exponent with increasing crack length for longitudinal leak openings. This could be due to the bell shaped crack at the end of the longitudinal crack on the AC pipes. However, Greyvenstein (2004) had tested too few pipes to come to an accurate conclusion.

The low leakage exponent of 0.41 is a result of the leak area decreasing with increasing pressure which happens when the circumferential stresses developed are more than double the longitudinal stresses. However, this would only occur in circumferential cracks. For this to happen to longitudinal cracks, the longitudinal stresses would have to be considerably larger than the circumferential stresses which is an unlikely possibility in the field. Further experimental work needs to be carried out on this scenario to fully understand the behaviour of different materials under these conditions.

Buckley (2007) used a different, water less approach to test the theory of hole expansion and leakage exponents. In his experimental setup, he used two hydraulic bladders in the pipe which were expanded with the help of an air pump. He fitted two blockages on the outer side of the bladders, one fixed to the frame and the other fixed to the pipe. When expanded, this would simulate both longitudinal and circumferential stresses, placing the pipe in a biaxial stress state. Figure 2.11 shows a detailed illustration of the experimental setup that Buckley (2007) used.

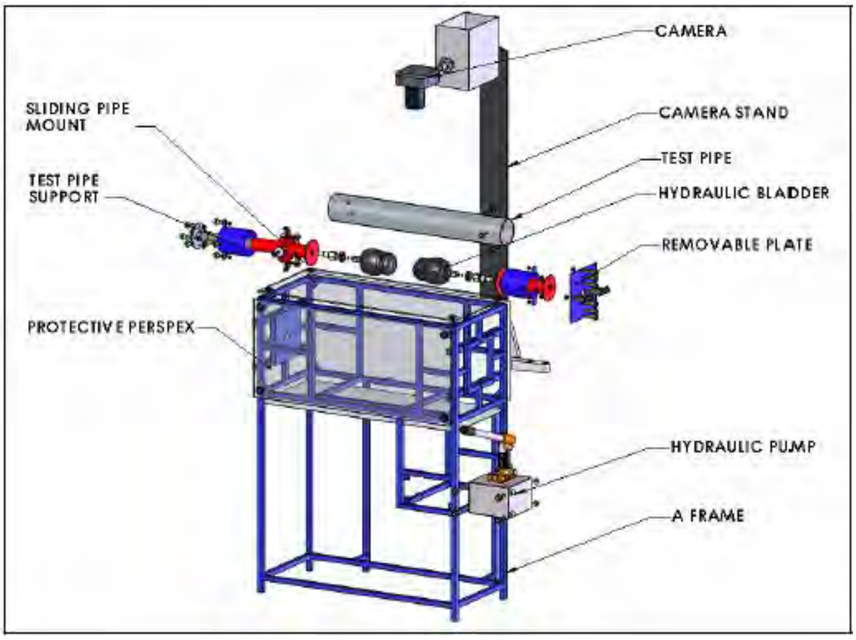

Figure 2.3: Exploded view of experimental setup (Buckley, 2007).

Buckley (2007) encountered a few problems during the calibration of his setup. The two bladders developed inconsistent pressures around the defected region, whereas a uniform pressure is required for best results. As a result, all the pipes in the biaxial tests only experienced 62% of the bladder pressure.

Buckley (2007) tested 4 different diameter holes (6mm, 8mm, 10mm and 12mm) of a class 6 uPVC pipe. There was an experimental error with the 8mm hole which was therefore excluded from the results. Regardless of this error, the results clearly showed an increase in the area with an increase in pressure, although the increase was relatively small. Figure 2.4 shows the different expansion rates for the 6mm, 10mm and 12mm hole which proves the linear relationship between pressure and area.

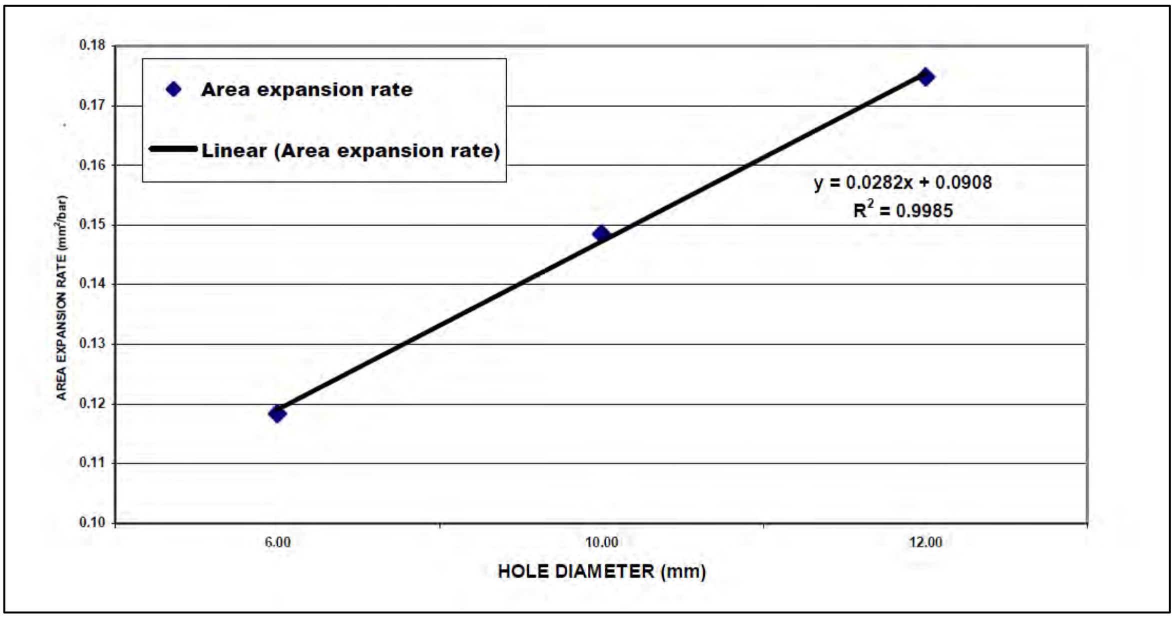

Figure 2.4: Area expansion rates plotted for different round hole diameters of a pipe (Buckley, 2007).

Buckley (2007) wanted to show that the orifice area increases with an increase in pressure, making flow sensitive to pressure, contrary to what the conventional method assumed. In his investigation he derived equations for increased flow though round holes in pressurized cylinder shells and pipes. The theoretical models incorporated material properties, shell geometry and fluid properties to explain the increased flow experienced during an increase in the orifice area. These results were compared to previous Finite Element Analysis (FEA) results.

Buckley (2007) also carried out an experimental investigation into the effects of pressure on round holes and longitudinal cracks on a class 6 uPVC pipe. The results showed a positive comparison with those of the theoretical equations. However, the results indicated that the round hole area is linearly related to pressure but that longitudinal cracks resulted in a non-linear relationship between crack area and pressure.

This increase in area would conflict with the conventional method of assuming the leakage exponent to be 0.5. Buckley (2007) shows this by plotting the flows for each diameter size against their respective pressures to determine the leakage exponent for each orifice. The results can be seen in Figure 2.5 which shows the leakage exponents of the 6mm, 8mm, 10mm and 12mm holes to be 0.5110, 0.5246, 0.5140 and 0.5091 respectively. All the exponents are close to 0.5 but not exactly 0.5. As explained in Table 2.2, even a small change in the leakage exponent can result in a large change in the leak flow.

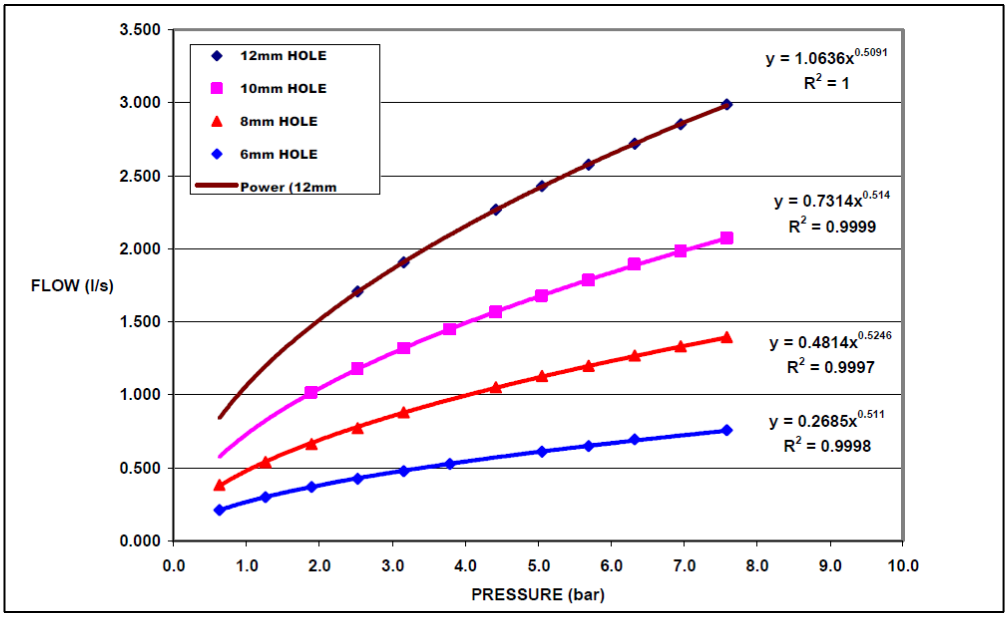

Figure 2.5: Flow relationships for different size defects plotted against pressure (Buckley, 2007).

Buckley (2007) also tested 3 longitudinal cracks of different lengths (40mm, 60mm and 90mm) using the same process. Table 2.5 shows a summary of the results attained. Note that for a longitudinal crack the rate of area expansion increases considerably with an increase in pressure.

Table 2.4: Summary of results for longitudinal cracks under biaxial stresses (Buckley, 2007).

Crack Length (mm)	Crack Width (mm)	Measured Crack Area (mm^2)	Rate of Area Expansion (mm^2/bar)	Leakage Exponent
40.0	1.2	49.5	5.6721	0.8413
60.0	2.0	126	18.458	0.7570
90.0	1.7	153	41.52	0.8579

The results show that longitudinal crack expands at a greater rate than round holes do. The length of the crack has an effect on the rate of expansion since the longer the crack length the greater the expansion rate. This is because the circumferential stresses are concentrated at the crack tips; therefore a longer crack will have greater stresses at its tips.

Figure 2.6 shows the flow versus pressure graph for each of the crack lengths. Once again it is clear that an increase in pressure will result in an expansion of the leak area and that this expansion has an effect on the leak flow as well as the leakage exponent.

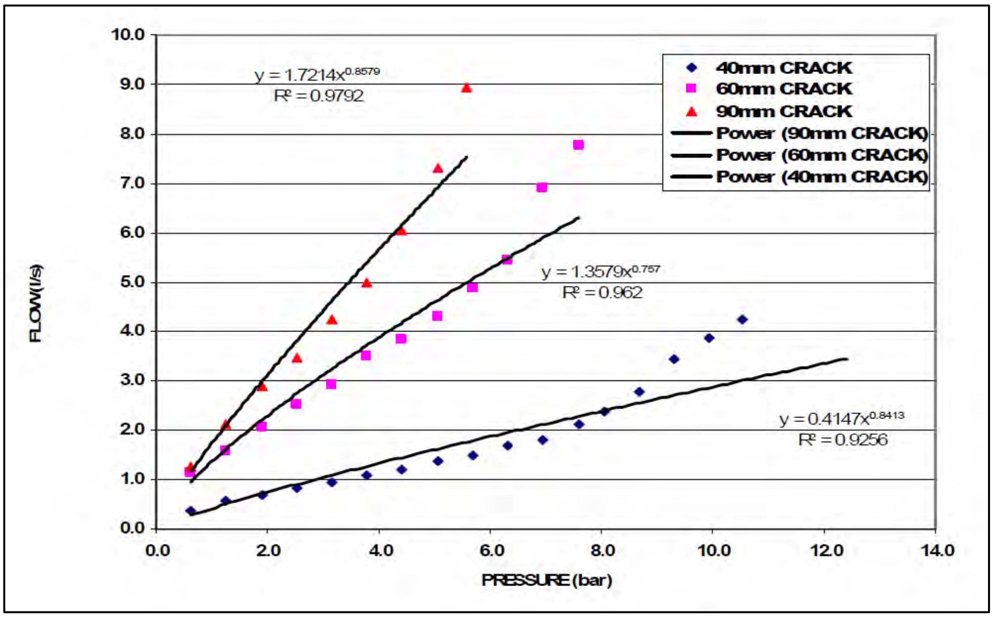

Figure 2.6: Flow vs pressure graphs for longitudinal cracks in uPVC class 6 pipe (Buckley, 2007).

2.2.1.3 Elastic Leak Behaviour Equation

A breakthrough in leakage control was achieved by May (1994) who adapted the orifice equation to produce the Fixed and Variable Area Discharge (FAVAD) equation. This equation consists of two terms: a flow term where the area does not expand as a function of pressure, and a flow term that takes into consideration the change of the area as a function of pressure.

The FAVAD equation was derived by firstly defining the relationship between area and pressure as being linear as shown by this equation:

$$A = A_0 + mh \tag{3}$$

Where A_0 is the initial area of the leak, m is the pressure-area slope and h is the pressure head. Replacing equation 3 into equation 1 gives equation 4:

$$Q = C_d\sqrt{2g}(A_0 h^{0.5} + mh^{1.5}) \tag{4}$$

Where $h^{0.5}$ term describes the flow through the initial fixed area of the leak and the $h^{1.5}$ term describes the flow through the expanded area of the leak. This equation is not a new equation and had been used by different researchers in the past. However, most of the other investigations assumed that the leaks were either fixed or variable and could not have both terms existing at the same time (Piller & van Zyl, 2014).

2.2.1.4 Predicting the Head-area Slope

The head-area slope (m) is an important leakage parameter that helps to understand the expansion behaviour of a leak. In the past, determining m values by using experimental methods was more common, but this was specific to the pipe that was tested. With a constant improvement in pipe materials, having to re-test pipe samples to determine m values would be inefficient. Instead, Cassa and van Zyl (2012) carried out research which involved a study to find a mathematical relationship between the behaviour of different crack types (longitudinal, circumferential and spiral) with pipe and leak parameters under different conditions.

A Finite Element Analysis was used to find a relationship between pressure and the leak area for different types of cracks. This was done by analysing the behaviour of the different cracks in pipes under high pressure. Each equation was then adjusted to fit their respective crack type.

Cassa and van Zyl (2012) used a regression analysis to obtain mathematical models showing the head-area slope (m) as a function of the pipe and crack parameters. The models helped to derive an equation of m for each crack type as shown by equations 5, 6 and 7 below:

$$m_{longitudinal} = \frac{2.93157 \times d^{0.3379} \times L_c{}^{4.80} \times 10^{0.5997(\log L_c)^2} \times \rho \times g}{E \times t^{1.746}} \quad (5)$$

$$m_{spiral} = \frac{3.7714 \times d^{0.178569} \times L_c{}^{6.051} \times \sigma_1{}^{0.0928} \times 10^{1.05\,(\log L_c)^2} \times \rho \times g}{E \times t^{1.6795}} \quad (6)$$

$$m_{circumferential} = \frac{1.64802 \times 10^{-5} \times L_c{}^{4.87992662} \times \sigma_1{}^{1.09182555} \times 10^{0.82763163(\log L_c)^2} \times \rho \times g}{E \times t^{0.33824224} \times d^{0.186376316}} \quad (7)$$

The above equations were developed based on the following parameters:

- Crack properties: orientation, length and width
- Pipe material properties: Young's modulus, Poisson's ratio and longitudinal stresses
- Pipe section properties: internal diameter and wall thickness.

The leakage number (L_N) is defined as the ratio between fixed and variable leaks. L_N can be determined using the head-area slope, head and initial leak area as shown by equation 8:

$$L_N = \frac{mh}{A_0} \tag{8}$$

Cassa and van Zyl (2012) also developed a mathematical relationship between the L_N and N1 which is shown by equation 9:

$$L_N = \frac{N1-1.5}{1.5-N1} \tag{9}$$

The above equations in conjunction with the pressure-area slope graphs can be used to predict N1 for various pipe materials with different parameters.

2.2.2 Behaviour of Leaks

The behaviour of a leak is a combination of three factors: Pipe material behaviour, leak hydraulics and failure types. This section will review relevant literature that focuses on these three factors.

2.2.2.1 Pipe Material Behaviour

Water distributions systems have been used for centuries and for this reason a large variety of pipes have existed in these systems for over a hundred years. A study by Mora-Rodriguez et al. (2013) showed that cast iron pipes were the most common material used at the beginning of the last century and dated some of the earliest cast iron pipe networks to the 1870s. Ductile iron pipes were the next favourite but were only introduced in the 1970s. There is also some evidence that Asbestos Cement (AC) pipes were used from the end of the 1920s to the beginning of the 1980s in Australia, Europe and North America. Polyvinyl Chloride (PVC) pipes were introduced in the 1970s as well but mainly in Europe and North America. It was not until the 1990s that Polyethylene (PE) was introduced as a pipe material and initially it was available as medium density (MDPE) and high density (HDPE).

Mora-Rodriguez et al. (2013) used the above information to develop a simple graph to show a visual representation of the commercialization of pipes in water distribution networks. This graph is shown in Figure 2.7.

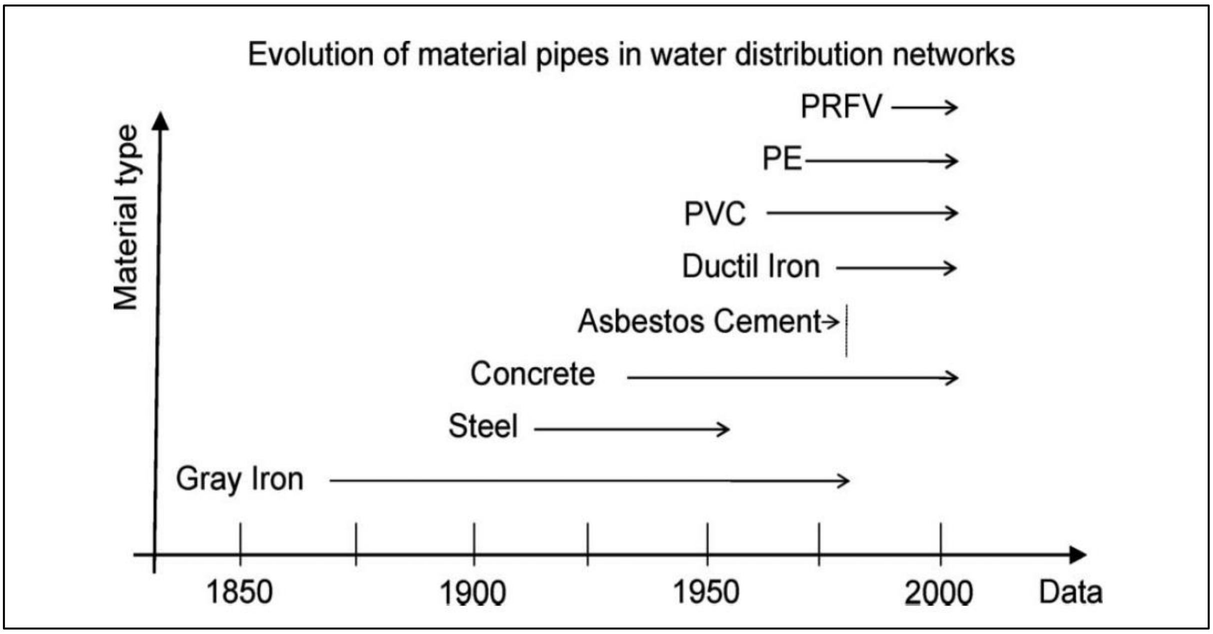

Figure 2.7: Commercialization of pipes in water distribution systems (Mora-Rodriguez et al., 2013).

Grey cast iron pipes were the most commonly used pipes up until the 1980s, and in 2001, 505 of North America's water distribution systems were comprised of grey cast iron pipes. It is, however, also the material that is most prone to failure, especially by corrosion (Markar et al., 2001).

Iron and ductile pipes were preferred due to an inner covering made of mortar cement and an outer covering painted with zinc and bituminous paint. This makes the material more corrosion resistant but corrosion is still possible. The soil surrounding the pipe material can induce electro-chemical corrosion on the outside of the pipe which is affected by the following factors: electrical currents, soil characteristics (humidity etc.), aeration and redox potential. Incrustations on pipe interiors can form when cracks or corrosion allow bacterial growth to take place (Mora-Rodriguez et al., 2013).

AC pipes are also sometimes reinforced. For medium pressure levels, normal steel reinforced pipes are used and for high pressure level pipes, post-tensioned concrete is suitable. Pre-stressed concrete was found to have a more probable leak occurrence. There are many chemical processes that cause deterioration of AC pipes. The surrounding soil could contain organic/inorganic alkaline, acids or sulphates that promote corrosion. Low soil pH can reduce the concrete's pH and result in weakening of the structure. Pipe age, diameter, water chemical, soil humidity, climate, and construction and maintenance also play a role in the structural integrity of an AC pipe (Mora-Rodriguez et al., 2013).

PVC has become the preferred pipe material in recent years because of the low price, and components and material properties. PVC has many advantages such as being a thermoplastic material, odourless, non-toxic, chemically inert, and corrosion and incrustation resistant. This allows the pipe sample to have a smaller wall thickness, better elastic deformation and therefore a lower chance of bursting with internal pressure. PVC does have some limitations however as it can't be exposed to the sun, which imposes complications during construction, and water temperatures can't exceed 45°C. The most likely deterioration to PVC occurs through mechanical deterioration, defective facilities, excessive operating conditions and damage due to external loading (Mora-Rodriguez et al., 2013).

PE in recent times has been made in two forms; low density (LDPE) and high density (HDPE). The MDPE discussed above is less common in recent years. PE is similar to PVC in its benefits (odourless, elastic, corrosion resistant etc.). Its low elastic modulus allows it to weaken water hammers and makes it a preferred choice in such situations and in spite of a large coefficient of thermal expansion; its flexibility is able to deformations and return to its original size under higher pressures. Mora-Rodriguez et al. (2013) were unable to find much information regarding the deterioration of PE pipes as they are still a recent introduction to networks.

2.2.2.2 Pipe Stresses

When considering a pipe as a cylindrical shell, both longitudinal and circumferential stresses develop within the walls of the pressurised pipe. These stresses are illustrated in Figure 2.8 which shows that the circumferential stresses (σ_1) are double the longitudinal stresses (σ_2). The circumferential stresses develop due to the internal pressure acting on the pipe wall, whereas longitudinal stresses develop from the internal pressure pulling the pipe apart in the axial direction (Buckley, 2007).

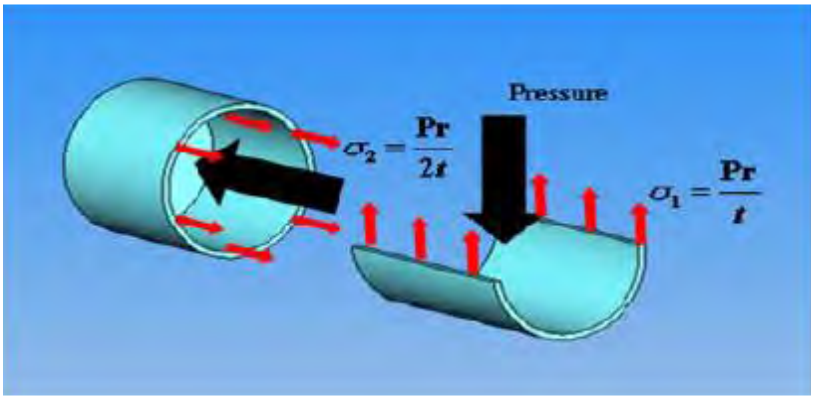

Figure 2.8: Stress distribution around a hole in a flat plate (Cassa et al., 2010)

The equations can be written more clearly for longitudinal and circumferential stresses as shown by equations 10 and 11 respectively, where P is the fluid pressure, r is the inner radius of the pipe and t is the pipe wall thickness.

$$\sigma_{Longitudinal} = \frac{Pr}{2t} \tag{10}$$

$$\sigma_{Circumferential} = \frac{Pr}{t} \tag{11}$$

A pipe can exist in two stress states: uniaxial and biaxial. Uniaxial stresses exhibit circumferential stresses but no direct longitudinal stresses, whereas biaxial stresses exhibit both circumferential and longitudinal stresses. The direct longitudinal stress present in the biaxial stress state can be brought about by a bend, valve or end cap (Buckley, 2007).

Clayton and van Zyl (2007) highlighted that an increase in stresses creates a strain on the pipe which often results in:

- the creation of new leaks
- the expansion of existing leak openings
- increased frequency of pipe bursts
- increased maintenance costs.

Figure 2.8 shows that the stresses in the circumferential direction are double those in the longitudinal direction. The presence of a discontinuity such as a circular orifice or crack increases the pipe wall stresses around the discontinuity. Clayton and van Zyl (2007) have shown that this circumferential stress around the discontinuity can be written as in equation 12:

$$\sigma = \frac{c'\rho g D h}{2t} = \frac{c'DP}{2t} \tag{12}$$

where σ is the pipe wall stress, c′ is a stress factor, D is the pipe diameter, ρ is the density, h is the pressure head and t is the wall thickness, which can be simplified further using h = Pressure $(P)/\gamma$. The stress factor accounts for the variation of stress around the hole and includes the stress concentration factor. If elastic behaviour is assumed, the circumferential stress can be written in terms of strain ε and Young's modulus E.

$$\sigma = \varepsilon E = \frac{\Delta d}{d_0} E \tag{13}$$

In equation 4, d_0 is the original hole diameter and Δd is the change in hole diameter due to the internal pressure of the pipe. The final hole diameter can be expressed as a sum of d_0 and Δd. Using equations 12 and 13, the final hole diameter can be expressed as shown by equation 14:

$$d = d_0\left(1 + \frac{c'\rho g D h}{2tE}\right) = d_0(1 + Ch) \quad (14)$$

where C is a constant. Using equation 14 to find the hole area (assuming the leak area is circular) and replacing it back into equation 1 gives an equation for leak flow through a circular hole, as shown by equation 15:

$$q = (0.125g)^{\frac{1}{2}}\pi C_d d_0^2(h^{\frac{1}{2}} + 2Ch^{\frac{3}{2}} + C^2 h^{\frac{5}{2}}) \quad (15)$$

Equation 15 shows us that there are three terms each with their own leakage exponents (0.5, 1.5 and 2.5). This is similar to the range of leakage exponents of 0.5-1.8 found in field investigations. Clayton and van Zyl (2007) found that when equation 15 is applied to a typical leak from a pipe, the terms with exponents 1.5 and 2.5 have a negligible contribution on the leak flow.

In general, different pipe materials behave differently due to their respective material properties. Clayton and van Zyl (2007) have summarised common types of failure and their respective pipe materials:

- longitudinal cracks are common in asbestos cement pipes
- corrosion holes are common in steel and cast iron pipes
- circumferential cracks occur due to pipe bending and are common in small diameter cast iron pipes.

In another study by Cassa et al. (2010), a numerical investigation was undertaken to determine the effect of water pressure on the leakage rate. The main objective of the study was to investigate the behaviour of different leak openings being tested for different pipe materials using a Finite Element Analysis (FEA). The different leak openings were limited to round holes and longitudinal and circumferential cracks. The pipe materials were limited to uPVC, steel, cast iron (CI) and asbestos cement (AC).

Four pipe material aspects were observed during this investigation. The first was the distribution of stresses within the vicinity of the leak opening. The second aspect was trying to find a relationship between pressure and the leak area. The third was the effect of the leak area and geometry on the behaviour of the leak. The final material aspect investigated was the implications of the first 3 aspects on the leakage exponent. Only elastic deformation was analysed in this study. This was induced by simulating internal pressure. No external loading conditions were considered.

To develop an understanding for the effect of leak openings on localised pipe behaviour, Cassa et al. (2010) reviewed previous relevant studies. One study by Timoshenko and

Goodier (1951) which focused on the theory of elasticity explained how a discontinuity such as a leak opening in a pipe wall will lead to an uneven distribution of stresses. The maximum stresses developed close to the vicinity of the leak opening are significantly larger than the stresses in the rest of the pipe. This was illustrated by the consideration of a flat plate with a small hole, as shown by Figure 2.9:

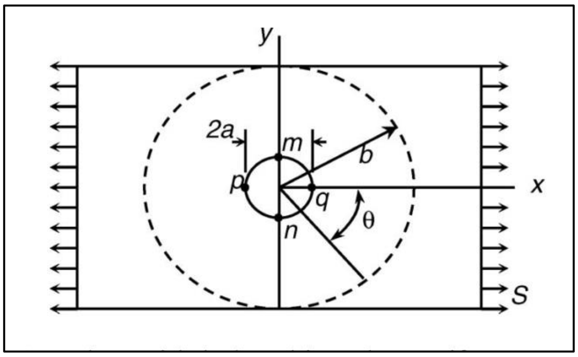

Figure 2.9: Plate with circular hole subjected to uniform tension (Cassa et al., 2010).

The plate is subjected to a uniform tensile stress of magnitude S (N/mm^2) along the x-axis. Only circumferential stresses are present at the edge of the hole. The circumferential stress can be determined by the theoretical equation below:

$$\sigma_{\theta} = S - 2Scos2\theta \tag{16}$$

This equation shows that the maximum tensile stress has a value of $3S$ and occurs at points m and n in Figure 2.9. Since the hole is localised, the bigger the distance from the hole, the quicker the stresses approach S. Point's p and q however experience only compressive stresses at a maximum size of S.

Figure 2.10 shows the distribution of stresses around the hole. Equations for the longitudinal and circumferential stresses can be derived and are shown by equations 17 and 18 below.

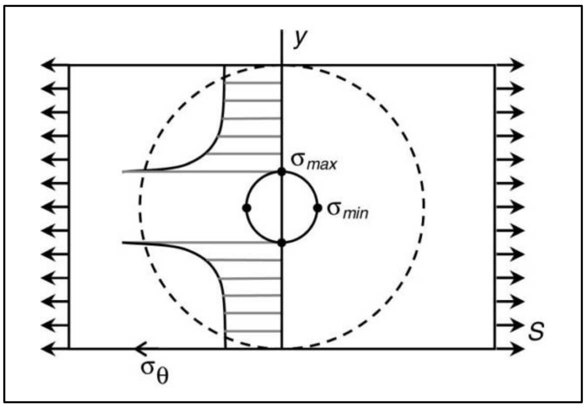

Figure 2.10: Stress distribution around a hole in a flat plate (Cassa et al., 2010).

$$\sigma_{Longitudinal} = \frac{Pr}{4t} \tag{17}$$

$$\sigma_{Circumferential} = \frac{Pr}{2t} \tag{18}$$

These equations are similar to equations 10 and 11 presented by Buckley (2007). Timshenko and Goodiers' (1951) equations show that the stresses are half that of the ones presented by Buckely (2007). In spite of the slight discrepancy, both methods prove that the circumferential stresses around a circular leak opening are double the longitudinal stresses when considering a circular leak opening.

The effect of a discontinuity on the behaviour of the material can be expressed using a stress concentration factor *K*, which is the ratio of the maximum stress to the nominal stress as defined by Gere (2001).

$$K = \frac{\sigma_{max}}{\sigma_{nom}} \tag{19}$$

For a flat plate with a round hole, the theoretical value of *K* is 3 using equation 19. However, this value is likely to be different for a pipe due to its curvature and the presence of longitudinal stresses. Replacing Figure 2.9 with a longitudinal crack shows that the highest stress concentrations are found at the crack tips. Considering linear elasticity means that an infinite stress is predicted for an ideally sharp crack tip. This situation does not exist in practice because plastic deformation and imposed external loads occur on the pipe. To account for this condition, a stress intensity factor K_I is introduced into the situation (Dieter, 1988):

$$K_1 = FS\sqrt{\pi a} \quad (20)$$

Where F is a factor that considers the geometry of the leak opening, S is the mean stress and a is the crack length. Equation 20 can be used in conjunction with the fracture toughness of a material to predict the possibility of a sudden propagation of the crack.

The FEA method consists of developing geometric models to assist in solving complex engineering problems. Cassa et al. (2010) used this method to test 3 leak openings (circular holes, longitudinal and circumferential) on four pipe materials (Asbestos Cement (AC), steel, Cast Iron (CI) and uPVC). The pipes were calibrated to match a class 6 uPVC pipe of 110mm outer diameter. This is because uPVC is a common pipe material used in modern water distribution systems. The class 6 uPVC has a working pressure of 600kPa and therefore wall thicknesses were determined on the AC, CI and steel pipes to accommodate this pressure while maintaining an inner diameter of 104mm. Safety factors of the pipes were adjusted to the South African National Standards (SANS) codes to accommodate the changes in wall thickness.

Ten-noded quadratic tetrahedron elements were used for the geometric model and two sensitivity analyses were carried out, one to determine the most effective length of the pipe, and the other to determine the optimal finite element sizes. The pipes are clamped down in the most effective directions (x, y and z) and an internal loading pressure is applied to develop a uniaxial loading state, followed by clamping the pipe down in the longitudinal direction to develop a biaxial loading state. Pressures used for testing were 200, 400 and 600 kPa. A summary of the pipe properties is presented in Table 2.5 below:

Table 2.5: Summary of properties and dimensions of pipes used for testing (Cassa et al., 2010).

Properties	uPVC	Steel	Cast Iron	Asbestos Cement
Modulus of elasticity, E (GPa)	3	200	100	24
Poissons ratio, ν	0.4	0.29	0.21	0.17
Yield strength, y (MPa)	50	200	207	22.5
Allowable Stress, σ (MPa)	10.4	99	52	8.4
Safety factor	4.8	2	4	2.67
Internal diameter (mm)	104	104	104	104
Wall thickness (mm)	3	0.314	0.603	3.7

Cassa et al. (2010) found that for circular holes the highest and lowest stresses occurred at the inside lip of the hole as shown by Figure 2.9. It was also found that the area around the hole expands outward while the hole itself is pulled into the pipe, creating an elliptical shape. Furthermore, all pipe materials displayed a similar stress distribution pattern.

The relationship between the stress concentration and the area of the hole diameter was found to be linear. Steel and CI had similar slopes although steel had a slightly higher stress concentration. AC and uPVC also had similar slopes (flatter slopes than steel and CI) but uPVC developed a higher stress concentration. The stress concentrations vary for different hole sizes, therefore it was found that uPVC and AC had higher stress concentrations with smaller holes (<3.4mm), whereas steel and CI have higher stress concentrations with larger holes (>10.2mm). Figure 2.11 has been extracted from Cassa et al. (2010) and shows the stress distribution around a hole.

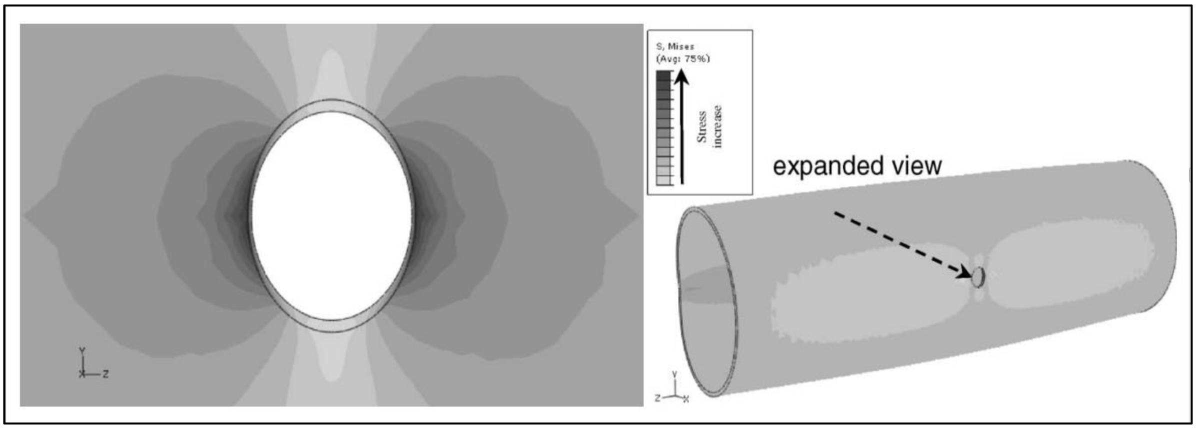

Figure 2.11: Stresses and scaled up (30 times) deformations around a circular hole (Cassa et al., 2010).

Since the maximum stresses at a hole can be significantly higher than the nominal stresses, the allowable stresses can easily be exceeded in the presence of a leak. Another important finding by Cassa et al. (2010) is that the yield strength of steel, CI, uPVC and AC pipes is surpassed when the hole diameters exceed 3, 13, 19 and 38 mm respectively. This is because at these diameters the localisation of stresses around the leak edges causes the stresses to increase above the yield strength of the material

For the longitudinal leak openings, the crack tips were modelled with a constant radius of 0.5mm. The stress distribution within the pipe is affected by the longitudinal opening and the highest stresses develop at the crack tips. Figure 2.12 shows the stress distribution around the leak opening and the geometry of the deformation:

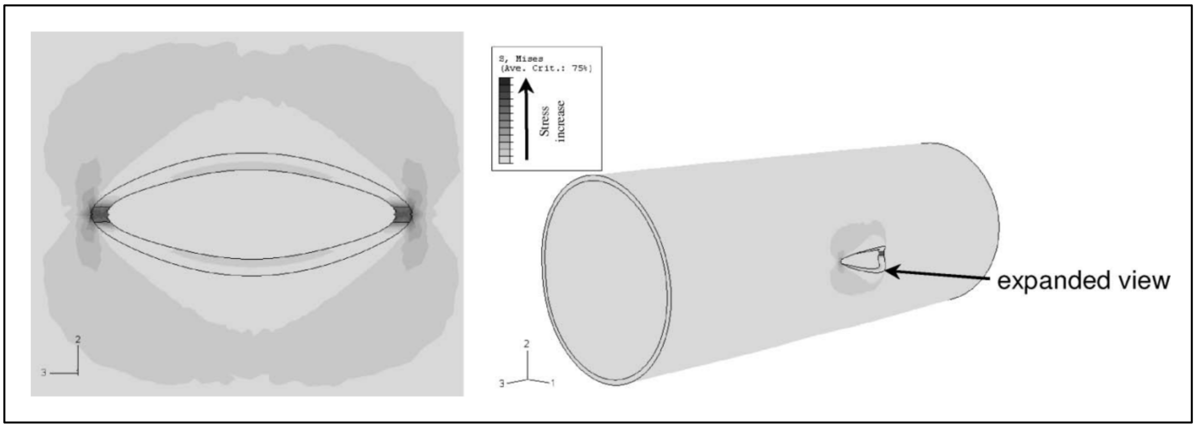

Figure 2.12: Stresses and scaled up (15 times) deformations around a longitudinal leak opening (Cassa et al., 2010).

Circumferential leak openings were modelled in a similar fashion to longitudinal leak openings with the crack tips at a constant radius of 0.5mm. The crack tips again displayed the largest stress concentration but the stress distribution pattern was different to that of the longitudinal leak opening. Figure 2.13 shows the stresses and deformation geometry of a circumferential leak opening in a pipe:

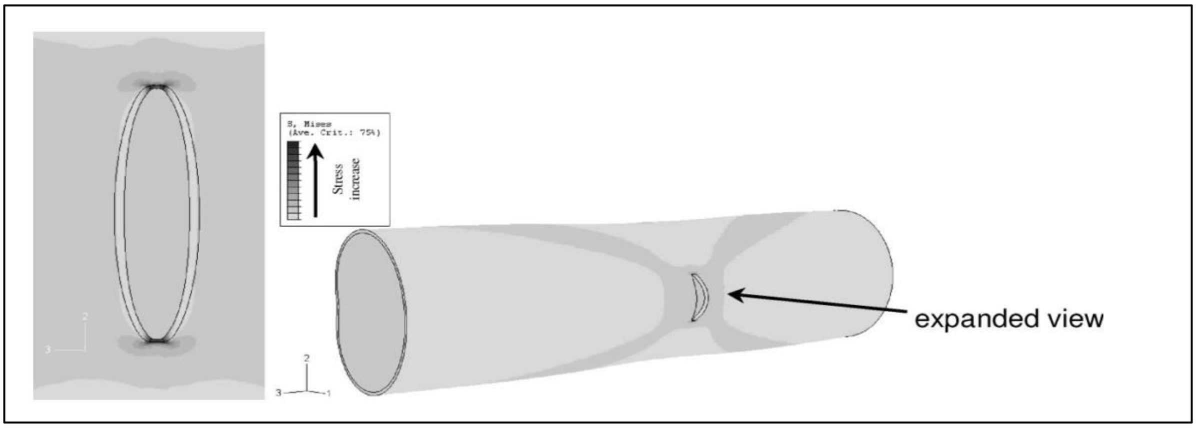

Figure 2.13: Stresses and scaled up (50 times) deformations around a circumferential leak opening (Cassa et al., 2010).

The leak openings were modelled with increasing pressure of 200, 400 and 600kPa and the increase in leak area noted. The pipes were modelled as class 6 uPVC which means a maximum operating pressure of 600kPa (59m). All the leak types displayed a linear relationship between increase in leak area and pressure head. Therefore the relationship can be described using the following equation (similar to equation 3):

$$A(h) = mh + A_0 \tag{21}$$

Where h is the pressure head, A is the leak area and A_0 is the initial leak area before any expansion has taken place. Replacing this equation in equation 1 develops an equation for the rate of leakage as a function of pressure:

$$Q = C_d\sqrt{2g}(A_0 h^{0.5} + mh^{1.5}) \tag{22}$$

This equation is the same equation proposed by May (1994) and explained in section 2.2.1.3, with the concept of fixed and variable areas where fixed areas have an exponent of 0.5 and the variable areas have an exponent of 1.5.

The linear relationship between leak area and pressure allows for better modelling of the system, which makes equation 22 more suitable than the commonly used equation 2. However, the exponents of 0.5 and 1.5 provide a range and limit to the leakage exponent, and therefore this equation is more applicable to a single, individual leak as opposed to a collection of leaks such as with in a water distribution network.

From Cassa et al.'s (2010) investigation based on modelling, the following points have been established as described below:

The first is that pipe stresses are significantly affected by leak openings especially in the areas closest to the leak opening (such as crack tips). In such areas the stresses can exceed the yield stresses of the material resulting in plastic deformation. The geometry of the leak opening has a significant effect on the stress distribution across the pipe.

The second point is that the leak area increases linearly with pressure until the elastic limit of the material is reached. Equation 22 gives a better description of this behaviour than equation 1, however it predicts a maximum exponent of 1.5 making it more suitable to describing an individual leak as opposed to a collection of leaks.

The third point is based on expansions. Round holes experienced the least expansion, followed by circumferential cracks. Longitudinal cracks showed the largest degree of expansion.

The fourth point is based on loadings states. It was found that under bi-axial states, both round holes and circumferential cracks experienced expansions. For round holes, the uni-axial loading state experienced much smaller expansions. For circumferential cracks, the uni-axial loading state resulted in a decrease in the leak area as opposed to an expanding one. Longitudinal cracks were not affected by the different loading states.

The final point made by Cassa et al. (2010) is that the effect of pressure on large leak openings increases exponentially with an increasing leak area.

The hydraulic behaviour of orifices has been researched extensively in the past. The N1 value of 0.5 is usually only true for large Reynolds numbers (Re). For lower Re values, equation 2 can be modified by expressing C as a function of Re. Alternatively, the variable coefficient can be written as a fixed coefficient with an exponent that is not 0.5. For transitional flow, the exponent will vary between 0.5, at the transitional-turbulent flow boundary and 1.0 at the transitional-laminar flow boundary (Clayton & van Zyl, 2007).

Re is an important dimensionless factor used when carrying out experimental investigations on fluid mechanics as it helps determine the turbulence of water flow. Re for a general leak can be written as follows:

$$Re = \frac{4vR}{\nu} = \frac{4q}{\nu P} \tag{23}$$

In equation 23, v is velocity, ν is the kinematic viscosity of the fluid, R is the hydraulic radius, q is the flow rate and P is the wetted perimeter. Kinematic viscosity can only be affected by two variables: temperature and the wetted perimeter of the orifice. The kinematic viscosity of water at 0°C is 1.787 x 10^{-6} m^2/s and at 30°C it is 0.801 x 10^{-6} m^2/s. Hence, the viscosity halves when increased from 0°C to 30°C, meaning that the maximum laminar or turbulent flow will double. Cracks have a larger wetted perimeter than circular holes of the same area and therefore will be able to sustain larger laminar or transitional flow rates (Clayton & van Zyl, 2007).

Ferrante et al. (2011) also carried out an investigation into leak hydraulics. The study explained the existence of two main issues that have affected water distribution systems over the past 10 years. The first is the relationship between the leak outflow and relevant factors such as leak geometry, pipe material and water head. The second issue is the effect of the governing equations on the pipe leakage.

Ferrante et al. (2011) focused the investigation on the second issue, based on an experimental study. The second issue can be explained as the effect of the leakage on the governing equations of flow in a pipe under pressure. This effect is related to errors on estimated parameter values such as pipe roughness and affects numerical models.

To define a simple leak through a pipe, a sketch was made based on the basic elements, as can be seen in Figure 2.14:

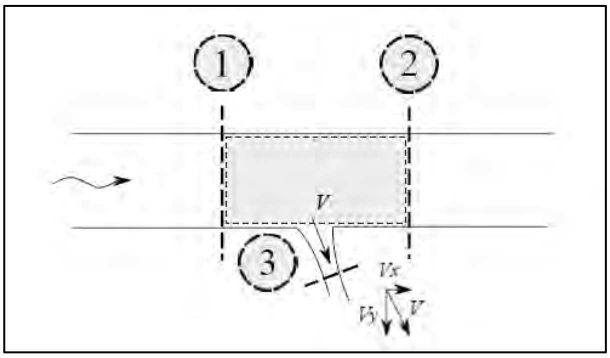

Figure 2.14: Definition sketch of pipe with leak (Ferrante et al., 2011).

The grey area is defined as a control volume. According to McNown (1954) and Bajura (1971), using the momentum equation with the control volume results in equation 24:

$$E = \frac{\frac{p_2 - p_1}{\Upsilon}}{\frac{V_1^2}{2g}} = 2r(2 - \Upsilon_d - r) \tag{24}$$

Here r is the flow through the leak (Q_3) divided by the flow at section 1 (Q_1), and p is the axial pressures at their respective sections. γ_d is the pressure regain coefficient which considers the axial momentum created by the leak flow. It is found by dividing V_x by V_1.

Ferrante et al. (2011) show that an alternative equation can be derived using the same quantities following the classical Bernoulli's approach. In this case the equation is written as:

$$E = r(2 - r) - \frac{h_f}{\frac{V_1^2}{2g}} = r(2 - r) - \gamma_f \tag{25}$$

Here h_f is the difference in head between section 1 and 2. Even though equation 25 uses the classical Bernoulli's approach, it does not represent an application of Bernoulli's theorem, instead it assumes that there is a head variation between section 1 and 2.

Ferrante et al. (2011) explain that Bernoulli's theorem for stream flow cannot be applied in this situation because the control volume is not a stream tube and the discharge varies between section 1 and 2 (due to the leak orifice). This is known as Borda head loss.

If an assumption is made that allows Bernoulli's theorem to be applied to the control volume, and there is no difference in head between sections 1 and 2 ($h_f = 0$), then equation 26 can be written as:

$$E = r(2 - r) \tag{26}$$

Whereas if equation 25 is used to evaluate h_f, then equation 26 becomes:

$$E = 2r(1 - r) \tag{27}$$

This makes equation 25 and 28 similar when $\gamma_d = 1$ which means that Bernoulli's theorem can be applied to the situation.

The experimental investigation was carried out by Ferrante et al. (2011) to try and validate the use of a proper equation. The experimental setup consisted of a 20 metre long HDPE (high density polyethylene) pipe that was fed water from one end with a pump and discharged into the atmosphere at the other end. The trunk had a longitudinal leak of 2 x 92 mm with rounded edges which also discharged into the atmosphere. There was a series of ball valves and butterfly valves used to control the flow. Electromagnetic flow meters and pressure transducers were used to record the flow and pressure both up and downstream of the leak. A drawing of the setup is provided in Figure 2.15:

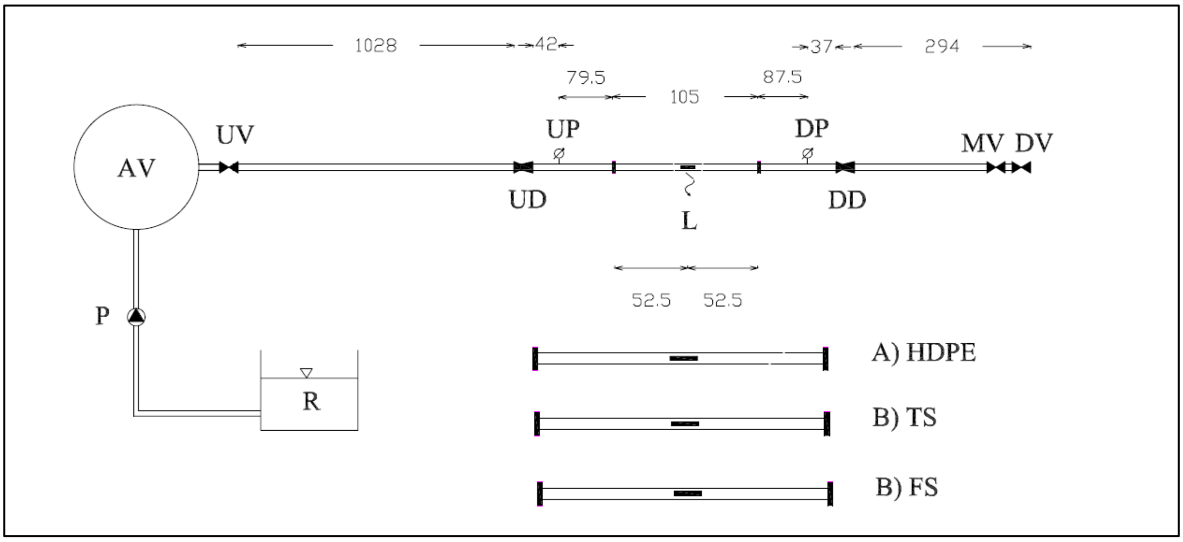

Figure 2.15: Experimental setup layout. R=recycling reservoir; P=pump; AV=air vessel; UV=upstream valve; UD (DD)=upstream (downstream) flow meter; UP(DP)=upstream (downstream) pressure transducer; L=leak; MV= automatically controlled butterfly valve; EV=end valve. Length in millimetres (Ferrante et al., 2011).

The results were derived from three sets of data. The first data set was used to compare the modified Euler number and head losses. The second and third comparisons were made between experimental values of γ_d and γ_f with their respective theoretical equations. A secondary investigation was also carried out on the angle of the leak jet. Pictures were taken that showed that the leak outflow angle ranged from 0° to 10°. The range is due to the hydraulic actions inside the pipe. When the water is allowed to flow out of the end of the pipe, the jet angle is at maximum, but when the water can only flow through the leak the jet is perpendicular as shown in Figure 2.16 below:

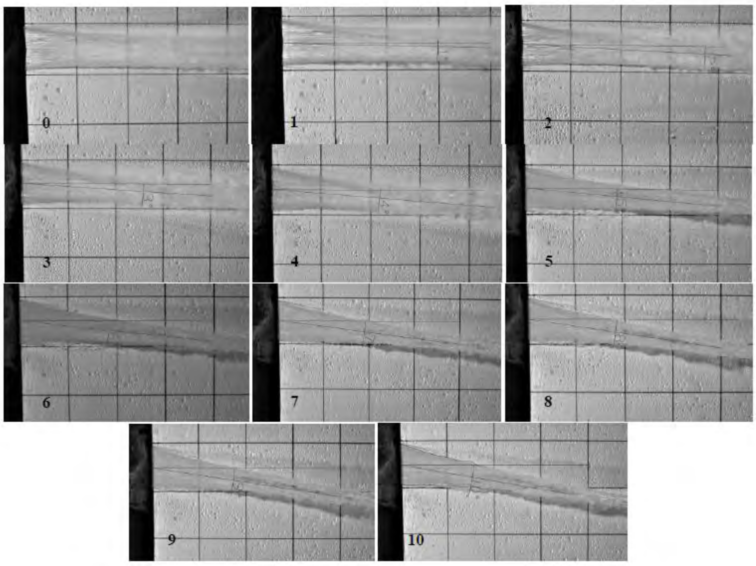

Figure 2.16: Pictures of the angled leak jet from Ferrante et al., (2011).

After analysis of all the sets of data, Ferrante et al. (2011) found that the use of the classical approach can be misleading. This is mainly because there could be a mass variation hidden in the head loss term which couldn't be accurately determined. Further work is required to investigate the mass variation component.

However, use of the momentum equation can also be misleading as it assumes that the leak jet is perpendicular to the pipe axis. Due to this angle, a term that accounts for this axial momentum needs to be found and included in the analysis. The results confirm that $\gamma_d < 1$ with the angle of the jet depending on flow conditions.

2.2.2.3 Types of Failure

In general, pipe failures are caused by excessive applied forces that diminish the residual strength of the material. Makar et al. (2001) have grouped the forces applied to water pipes into 5 categories: internal water pressure, bending forces, crushing forces, soil movement and temperature induced expansion.

Mora-Rodriguez et al. (2013) have a similar concept but have categorised the types of failure as a result of three main mechanisms:

- structural properties, material properties, soil interaction and facility quantity
- internal loads due to internal operation pressure and external loads due to ground loads
- material deterioration.

When pipe deterioration occurs, it happens in form of either structural deterioration or interior surface deterioration. Structural deterioration results in the diminished elasticity and ability to support loads. Inner surface deterioration leads to the the hydraulic capacity diminishing, resulting in degradation of water quality and a decrease of structural resistance.

Mora-Rodriguez et al. (2013) have classified 5 types of failure: longitudinal, circumferential, holes, joints, and others. This is commonly found in most of the literature reviewed, apart from spiral cracks which are discussed by Cassa and van Zyl (2012). Mora-Rodriguez et al. (2013) consider spiral cracks to be a type of longitudinal crack, whereas Cassa and van Zyl (2012) consider a spiral crack to be a crack at 45° to longitudinal and circumferential cracks. Makar et al. (2001) distinguishes 6 types of failure modes: blow out holes, circumferential cracking, bell splitting, longitudinal cracking, bell shearing and spiral cracking.

Circumferential cracking is the most common failure mode for small diameter pipes. Circumferential cracks are developed due to an increase in longitudinal tension. This is brought about by thermal contraction at low water temperatures, tension due to inadequate ditches and poor bed installations, external factors such as breakage or vandalism and soil movements producing longitudinal stresses (Makar et al., 2001; Mora-Rodriguez et al., 2013).

Longitudinal cracks are more common in larger diameter pipes and are caused by radial tension induced by internal pressure, ground loads, traffic and freezing of soil (Makar et al., 2001 & Mora-Rodriguez et al., 2013).

Circular leaks are usually as a result of corrosion and therefore are most common in metal and AC pipes (Mora-Rodriguez et al, 2013). Makar et al. refer to circular leaks as blow out holes which are more common in metal pipes. As the corrosion thins the pipe wall diameter, at a certain stage the internal water pressure will break through the pipe wall resulting in a blowout (Makar et al., 2001).

Joints are generally weak points in a network and therefore are affected by internal and external loads. Mora-Rodriguez et al. (2013) has not discussed the others failure types and therefore it is unclear what other types of failure may exist. Makar et al. (2001) explain that bell splitting is a common failure mode in cast iron pipes. This is due to a manufacture flaw as in the 1930s the joints of cast iron pipes were made by usinga bell as a mould. Recently, a non-metallic compound called leadite was used when casting and consequently at low temperatures this compound becomes brittle and cracks at the joint in a bell shaped manner.

Makar et al. (2001) also discuss bell shearing as a form of failure type. This is more common in large diameter pipes where a high moment of inertia induces circumferential failure at the joints. This type of failure in combination with an external load can cause the crack to propagate down the length of the pipe, resulting in a large failure.

Spiral cracking is another common failure type. It starts out as a circumferential crack but propagates in the longitudinal direction due to the internal pressure of the pipe. Bell shearing and bell splitting can be a result of spiral cracking.

2.2.3 Soil Hydraulics

Understanding the soil interaction of a leak is another important factor when considering leak hydraulics. Water moves through the soil by means of seepage. To do this it has to overcome the friction on the contact surface between the water and the pore spaces of the soil. The force which resists this frictional force is called the seepage force. The flow through the soil can either be laminar or turbulent. Laminar is considered to be a smooth motion of water particles in a parallel path where the water flow lines never intersect. Turbulent flow is a non-linear complex flow that results in carrying velocity and direction (Spangler & Hardy, 1982).

Clayton and van Zyl (2007) have shown that the seepage theory contradicts equation 1 because it shows that the flow rate should be linearly proportional to the water pressure in the pipe. According to Darcy's law, the flow rate in the soil at the water-soil boundary is given by equation 28:

$$q = Fkh \tag{28}$$

Where q is the flow rate, F is the form factor for the soil flow region, k is the coefficient of permeability and h is the water head in the pipe. Even though equation 23 is based on the seepage rate of water through a soil, Clayton and van Zyl (2007) have highlighted some underlying assumptions that are not valid for seepage around a water pipe:

- The velocity component of the total head, in seepage analysis, is very small and can be ignored. In general, the velocity of flow through a soil depends on the coarseness of the soil. Clean coarse sands have a higher velocity (approx. 10^{-2} m/s) whereas clays have a lower velocity (approx. 10^{-8} m/s). Equation 1 (Orifice Equation), however, predicts very high velocities at the water-soil boundary. A clear relationship cannot be defined by equating equation 1 and equation 8, showing that there is an incompatibility with this assumption.
- There is a fixed, upstream boundary geometry with constant head applied to it. Due to the high orifice outlet velocity, the boundary geometry and constant head will almost certainly be modified by both scour and fluidisation.
- Upstream and downstream boundaries have fixed geometries and head conditions. The position of any phreatic surface is also fixed. Water pipes are generally laid above the ground water level and therefore the form factor (F in equation 28) varies as a function of the orifice flow rate and permeability of the soil. In any soil medium, an increase in flow results in a build-up of pore pressure which will eventually lead to a build-up of water above the pipe. In general, depending on the soil type, if the leak flow rate is low relative to the permeability of the soil, then the water will not reach the surface and leakage will go unnoticed. If the leak flow rate is high relative to the permeability of soil, then water will break the ground surface and a burst will be detected.
- According to Darcy's Law, a linear relationship between head difference and flow is only valid for laminar flow. In soil, the discharge velocity is dependent on the hydraulic gradient and the permeability of the soil. Low hydraulic gradients are common in many seepage situations. In this case, laminar flow is expected in sands

and finer materials but not gravels, for low Reynolds numbers. Around a leaking pipe, however, the hydraulic gradient is higher and therefore non-laminar flow can be expected in most coarse soils and loose backfill material.

- For Darcy flow calculations, constant permeability is assumed with flow distributed across the entire region of permeable soil. For a particulate material the maximum pore pressure cannot exceed the stress on that plane. The stress would be a result of external loading and the self-weight of the soil. This is different from the effective stress which governs the strength and compressibility of a soil. If the pressure at any point in the ground rises above the minor total principal stress then hydraulic fracture takes place. In this situation, cracks form in the soil along planes of weakness causing the flow rates to increase and making seepage analysis impossible. The flow along these cracks is likely to be non-laminar and as the head increases, the transition to hydraulic fracturing contributes to leakage exponents greater than unity. Even if hydraulic fracture does not take place but upward flow occurs in unbounded granular soil, the velocities increase and fluidisation may occur. This is commonly referred to as 'piping' and occurs when the upward force of the soil particles surpasses the soils buoyant self-weight, resulting in a hydraulic gradient equal to unity.

2.3 Summary of Literature

The literature showed that the relationship between leakage and pressure is complex. The expansion and contraction of leak areas varies between crack geometries. Pipe material and leak hydraulics also have a large influence on the behaviour of leaks. The investigations by Buckley (2007) and Greyvenstein (2004) give good insight into the development of an experimental procedure to determine leakage parameters, which will be presented in the following chapter.

3. Developing a Methodology

This chapter reports on the development of a standard experimental and analytical procedure to determine N1 values for an individual leak in a pipe. Firstly, a description of the available resources in terms of equipment and environment are given; this is followed by a discussion of the calibration of the instruments that were used. Thereafter, the experimental procedure data analysis method is described in detail. The procedure and method were tested for consistency and efficiency, then adjustments were made to improve both procedure and method. This final procedure and method was then used to test a series of pipes; this is described in Chapter 4.

3.1 Experimental Environment

All the experiments were carried out at the University of Cape Town's Civil Engineering Laboratory. The laboratory contains a hydraulic section which consists of a drainage floor, underground reservoir and pump system.

The drainage floor is rectangular with an approximate length of 8 metres and a width of 5.5 metres. The floor is surrounded by a drainage trench which directs water into the underground reservoir. Figure 3.1 shows the drainage floor with some of the experimental apparatus used at the time.

Figure 3.1: Picture of the hydraulics section of the Civil Engineering Laboratory at the University of Cape Town.

The underground reservoir contains a 9.2kW stainless steel submersible pump which has a duty of 5 l/s at 100 metres of water head. This means that the pump is at peak output (50 Hz) when delivering 5 l/s with an equivalent pressure of 10 bar. A pump curve is provided in Appendix A of this report. Water is pumped from the reservoir into a copper pipe network that is mounted to the wall.

The pipe network has two electro-magnetic flow meters (DN 15 and DN 25) which can be isolated depending on which one is required for usage. The DN refers to the diameter of the flow meter of 15mm and 25mm respectively. The working flow range for the DN 25 and DN 15 are 0-5 l/s and 0-1.77 l/s respectively. Both the flow meters have a repeatability of ± 0.1%. Both flow meters have an accuracy of ± 0.5% of rate for velocity when greater than 0.5m/s and ± 0.025% of rate of velocity when< 0.5m/s. A calibration data sheet is provided in appendix A of this report.

The network is also connected to the municipal water supply inlet which can be fed into the flow meters in a similar fashion to the water from the reservoir. There is a series of non-return valves and shut-off valves which stop any water from flowing back into the reservoir or municipal water inlet. Any water that is spilled on the drainage floor will run back into the reservoir and can be pumped back into the wall mounted network; this allows for a sustainable use of water. Figure 3.2 shows a picture of the copper network and flow meters setup by the manufacturer.

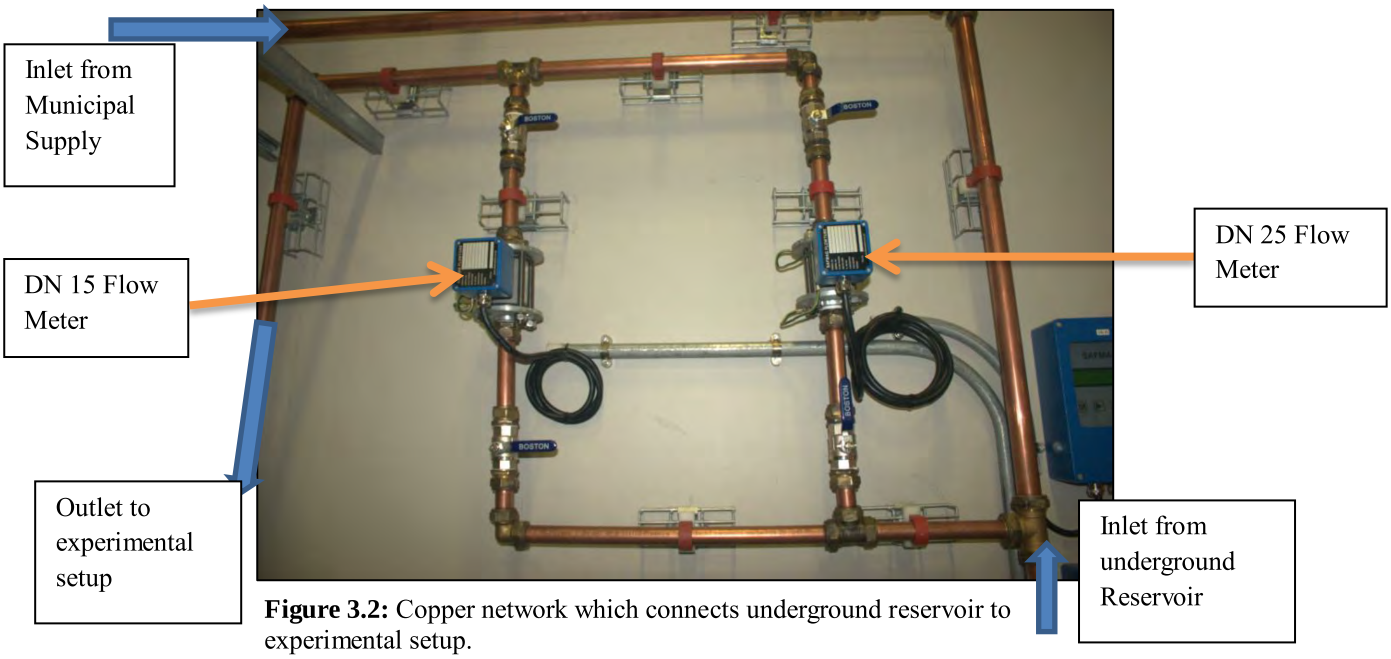

Figure 3.2: Copper network which connects underground reservoir to experimental setup.

Figure 3.3 shows a schematic diagram of the copper pipe network.

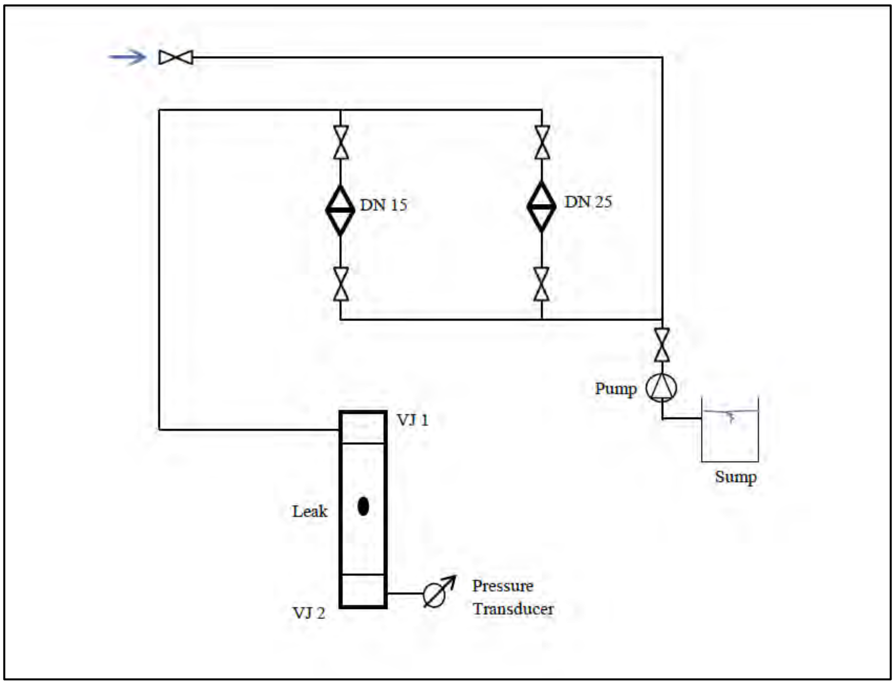

Figure 3.3: Schematic diagram of copper pipe network.

3.2 Experimental Setup

The experimental setup required constraining a pipe with a leak under high internal pressure so that both flow and pressure readings could be acquired. To do this, the setup needed an inlet flow from the copper network to fill up the pipe with water as well as a connection to a pressure transducer for taking pressure readings. This was done by designing two end pieces. Each end piece was constructed using high density uPVC plates with a thickness of 25mm. A class 9, 110mm uPVC pipe section of 180mm length was connected to the uPVC plates. The other end of the uPVC pipe was connected to a Viking Johnson (VJ) coupling which would later be connected to the pipe sample being tested. The uPVC pipe section had a saddle with a hole drilled through to allow for an inlet flow in one end piece, and a pressure transducer connection in the other end piece. Figures 3.4 and 3.5 show pictures of the individual end pieces.

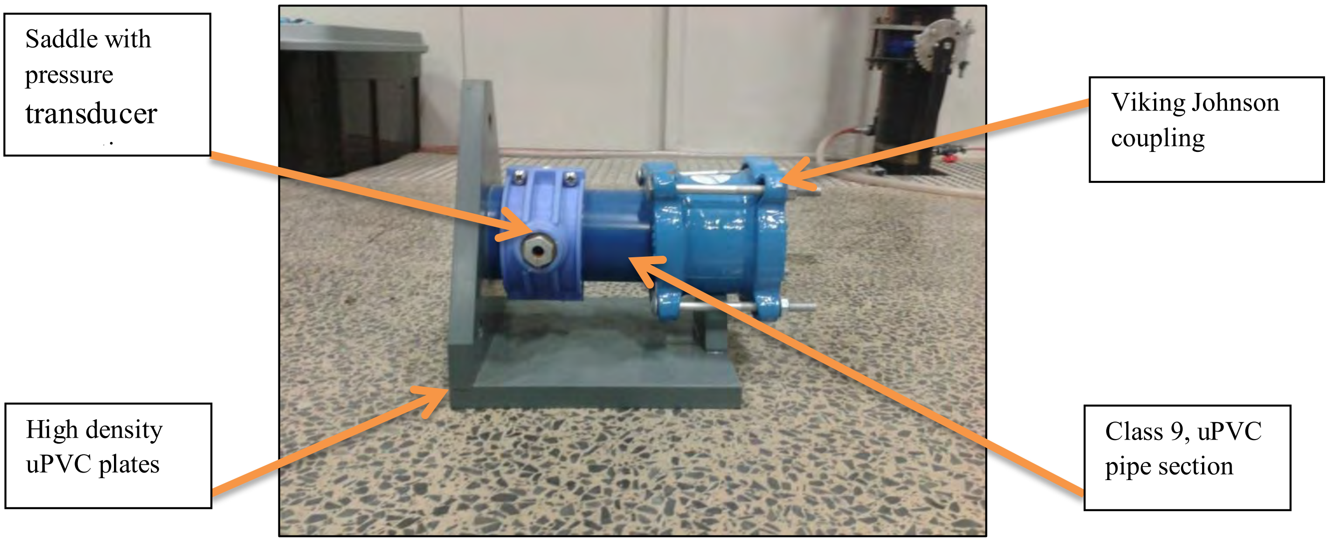

Figure 3.4: End piece with pressure transducer connection.

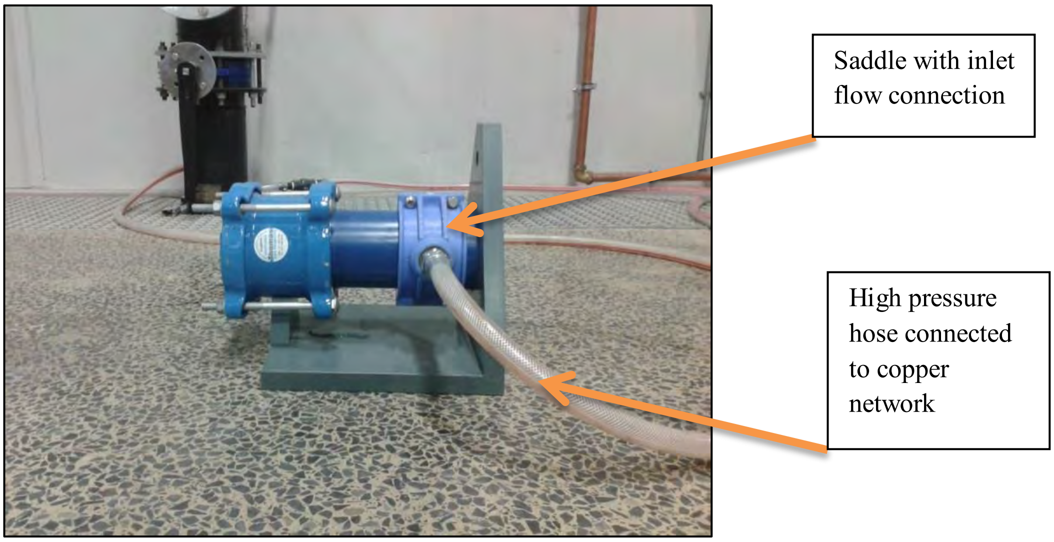

Figure 3.5: End piece with inlet flow connection.

A pipe sample was connected in-between the two VJ couplings. The VJ couplings do not provide enough tension restraint to keep the pipe sample in place under high pressure; therefore three stainless steel rods were used to provide sufficient restraint to the setup. This method is similar to that used by Greyvenstein (2004), the only difference being that the steel rods are tapped through the uPVC plates for this experimental setup, as opposed to threaded through the VJ couplings as done by Greyvenstein (2004). The reason for this is to allow a larger range of pipe lengths to be tested, as well as to allow the use of thicker steel rods which increase the working pressure of the setup. The minimum and maximum pipe lengths ranged from 400mm to 1800mm.

Two Sensus data loggers were used to take the readings. Each logger was connected to a flow meter and pressure transducer using a 4-20mA loop. The DN 25 was chosen for these experiments because of the larger working pressure range as explained in section 3.1. The pressure transducer used was Sensus Pressure Transducer with a working range of 0 - 20 bar at an accuracy of ± 0.5%. Figure 3.6 shows the completed experimental setup before the start of testing.

Figure 3.6: Experimental setup before the start of testing.

The maximum shut off pressure was determined to be 11.55 bar. This was found by adding a uPVC class 9 pipe, with no leak orifice, and increasing the pump speed to generate the maximum flow. Each of the steel rods has a yield strength of 200 MPa, which amounted to a total maximum yield strength of 600MPa for the experimental setup. Any longitudinal stresses placed on the end pipes were transferred to the steel rods. This yield strength was much higher than the maximum shutoff pressure but the most likely place for failure would be the pipe sample around the vicinity of the leak. Therefore the maximum allowable stress for the setup was assumed to be equal to the maximum working pressure of the pipe sample.

3.3 Calibration of Instruments

The pressure transducer and magnetic flow meter were the only two instruments that needed to be checked for correct calibration.

3.3.1 Calibration of Pressure Transducer

There are various methods of calibrating pressure transducers, depending on their sensitivity. The South Africa Synthetic Oil Liquid (SASOL) fuel testing lab at the University of Cape Town, has a Druck PV 62x Pneumatic/Hydraulic Pressure Station which can be used to test the calibration of pressure tranducers ranging from 0 to 100 bar which works for the SENSUS Pressure transducer. Figure 3.7 shows an image of the pressure station.

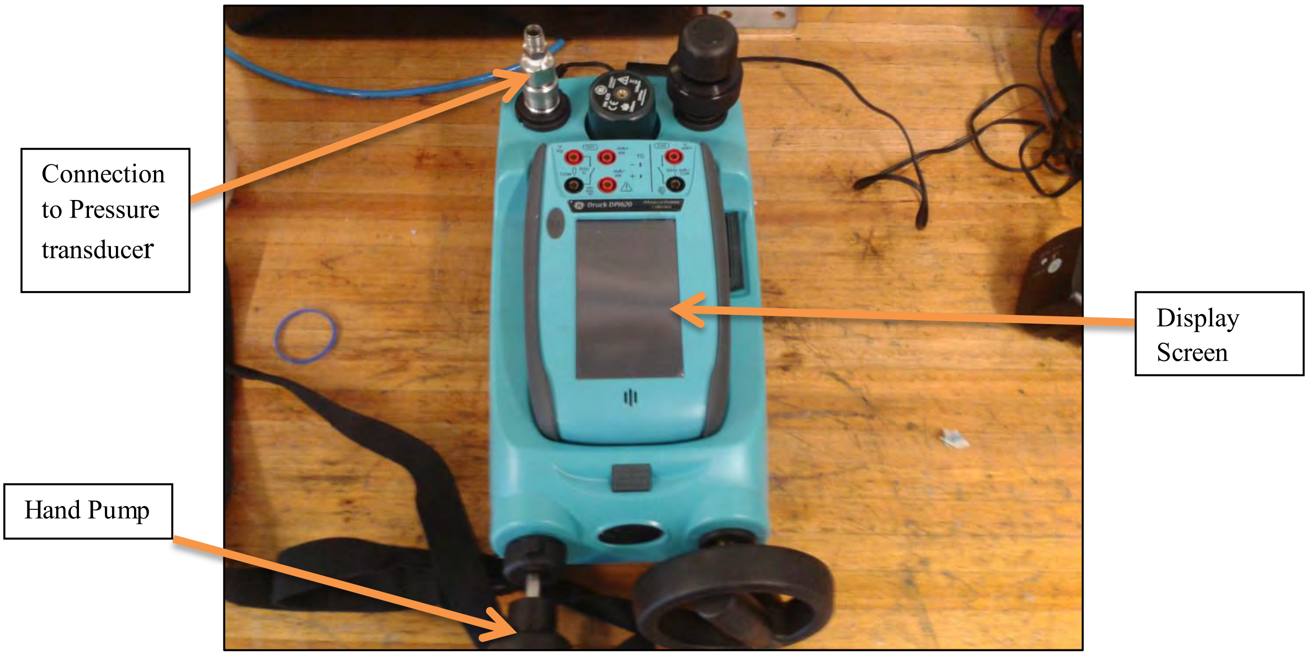

Figure 3.7: Druck PV 62x Pneumatic/Hydraulic Pressure Station.

The pressure transducer is connected to the pressure station via a nozzle (using 4-20mA loop) as shown in Figure 3.6 above. A hand pump is used to increase the pressure induced by the pressure station, which is then displayed on the display screen to 4 decimal places with 0.02% accuracy. This reading is then compared to the reading displayed on the pressure transducer. Since the SENSUS Pressure Transducer does not have a display screen, it was connected to a data logger which has a display screen that shows values to 2 decimal places. Table 3.1 shows the results from the calibration test.

The results show that the SENSUS Pressure Transducer is calibrated correctly to 2 decimal places.

Table 3.1: Results of the calibration test done with the Druck Pressure Station.

Pressure Transducer Readings (Bar)	Pressure Station Readings (Bar)	Error (%)
0.69	0.69	0
1.58	1.58	0
2.39	2.39	0
4.56	4.56	0
6.53	6.53	0
8.33	8.33	0
9.78	9.78	0
10.40	10.40	0
12.96	12.96	0
13.99	13.99	0
14.50	14.50	0
15.36	15.36	0
16.59	16.59	0

3.3.2 Calibration of Electro-magnetic Flow meter

The electro-magnetic flow meters were a recent purchase by the University of Cape Town and both flow meters were accompanied by their calibration certificates. The DN 25 flow meter was used in this experiment and the calibration certificate is attached as Appendix A of this report.

When initially connecting the data logger to the flow meter it was found that the data collected by the logger and the data displayed on the display screen of the flow meter were inconsistent. Further attempts were made to re-programme the data logger but none of the attempts were successful in matching the flow meter data to the one collected by the data logger.

A further investigation was carried out to try and find a relationship between the two sets of flow values. 17 readings were taken from the flow meter and the logger collected for comparison. Table 3.2 shows the displayed flow meter readings and the collected logger readings.

Table 3.2: Flow meter readings and their equivalent readings collected by the data logger.

Sample #	DN 25 Flow Meter (l/s)	Data logger Flow (l/s)
1	1.4515	3.0142
2	1.6978	3.5105
3	1.8918	3.9074
4	2.2448	4.6228
5	2.4672	5.0559
6	2.2906	4.7019
7	1.9245	3.9781
8	1.7000	3.5253
9	1.3295	2.7849
10	1.6978	3.5191
11	1.8525	3.8383
12	2.1947	4.5189
13	2.4628	5.0565
14	2.2536	4.6367
15	1.8874	3.9065
16	1.7000	3.5244
17	1.5910	3.3056

The data in Table 3.2 clearly shows a linear relationship which is presented in Figure 3.8. The relationship is given by the flowing equation:

$$Q_{DL} = 2.0056Q_{FM} + 0.1123 \tag{19}$$

Here Q_{DL} is the flow collected by the data logger and Q_{FM} is the flow displayed on the flow meter display screen. Q_{FM} is required for the calculations therefore every time flow data is collected by the logger it will need to be converted back to the displayed flow meter value using equation 20 edited below.

$$Q_{FM} = \frac{Q_{DL}}{2.0056} - 0.05599 \tag{20}$$

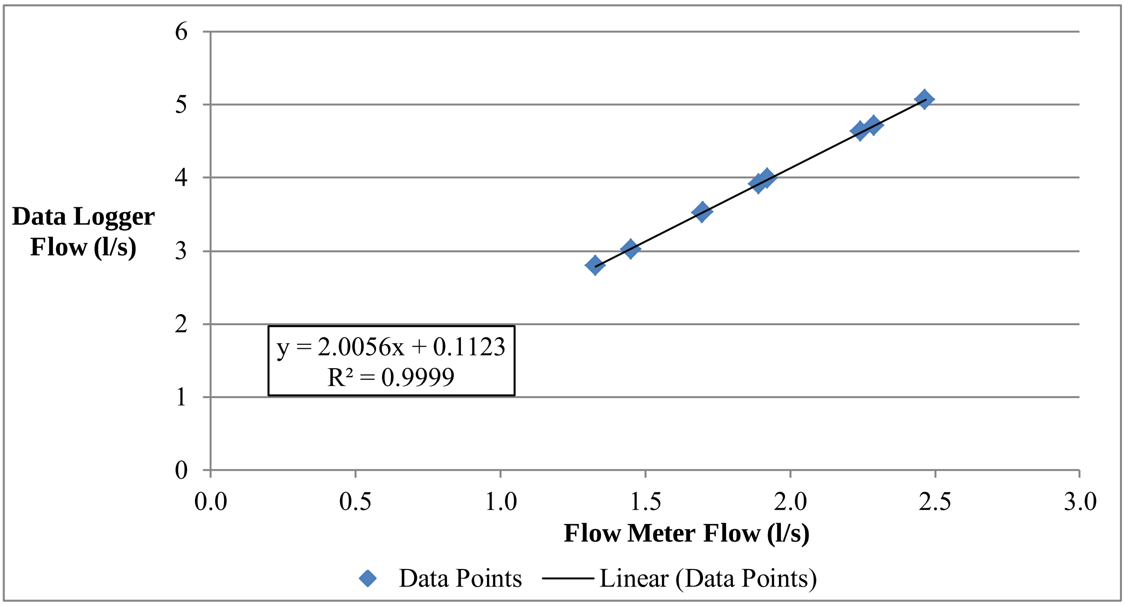

Figure 3.8: Linear relationship between displayed flow meter values and collected logger values.

The reason for this inconsistency may be due to the 4-20mA cable used to connect the data logger to the flow meter. The information sheet provided with the flow meter (attached as Appendix B) states that this cable needs have the correct length and should be provided by the flow meter supplier. Unfortunately, the required 4-20mA cable was not provided by the supplier. An alternative 4-20mA cable was used and it is assumed that this cable was not of the correct length and affected the electromagnetic signal emitted by the flow meter. An attempt was made to acquire another 4-20mA cable to test the length difference but these cables are expensive and have a long shipping duration.

3.4 Current Experimental Procedure and Data Analysis Method

This section gives a detailed description of the procedures followed before the start of the experiment, during the course of the experimentation, and after completion of the experiment.

3.4.1 Pre-Experimental Procedure

The first step taken was the connection of the pipe sample into the setup. This was done by lining up the end pieces and fitting the pipe sample into the VJ couplings, ensuring that the leak orifice was aligned with the inlet flow and pressure transducer connections. The nuts and bolts of the VJ couplings were tightened until the pipe sample was secured in its place. The steel rods were then fitted through and fastened to the end pieces on both sides, one side is using a lock system, and the other side using a thread and nut system. The lock system allows the pipe length to be adjusted with 100mm increments. The thread and nut system allows the length to be varied within the 100mm increments. This allowed for any pipe length in the range 400mm to 1800mm to be tested.

The next step was the programming of the Sensus data loggers. The data loggers were connected to a computer using a USB-to-serial converter cable. The software programme CDLWin 4.0 was used to modify the logger parameters. For the logger connecting to the pressure transducer, the parameters were set to take readings in bar every second. For the logger connecting to the magnetic flow meter, the parameters were set to take readings in litres/second (l/s) every second. Both loggers had their internal clocks set to the same time as the computer clock to the nearest second. Once programmed, the loggers were connected to their respective meters.

Water then had to be filled into the setup and all air had to be removed. The presence of trapped air under the pressure transducer's sensor would have caused the pressure readings to vary resulting in inconsistent data. The inlet flow pipe was connected to the end piece but the pressure transducer was left disconnected from the setup. The setup was tilted around the horizontal axis of the pipe until the leak orifice and pressure transducer connection were facing vertically upwards.

Figure 3.9: Experimental Setup under weighted plastic box during testing.

Water was then pumped into the setup until it overflowed from the leak orifice and pressure transducer connection. The pressure transducer was then connected to its connection on the end piece. This step was important as no air should get trapped under the pressure transducer. The end piece with the flow inlet was then raised and lowered vertically, followed by the pressure transducer end piece being raised and lowered vertically. The raising and lowering technique was repeated 2 or 3 times and forces trapped air to come out of the leak orifice. Once a steady, consistent stream had been developed during this vertical motion, it can be assumed that all the air had been expelled from the setup. The setup was finally tilted back to its upright position, before the pipe sample was covered with a weighted plastic box. The weighted plastic box was used to contain the spray from the orifice which was under high pressure. Figure 3.9 shows an image of the running experimental setup under the weighted plastic box.

3.4.2 Data Collection Procedure

The pump speed (hence flow and pressure) can be increased using a Variable Speed Drive (VSD) located on the Human Machine Interface (HMI). The pump speed was increased incrementally in a step up manner. Each step was maintained at level for a period of 30 seconds. This happened for 5 steps (the fifth stage being the maximum pump speed) before being brought back down incrementally in a similar fashion. Flow and pressure readings were collected every second by the data loggers. This creates a step up and step down pattern for pressure and flow against time. Each pipe sample underwent this process three times consecutively. This method has been adopted from Greyvenstein (2004).

The total data collection time for one pipe sample was 12 minutes and 30 seconds.

3.4.3 Post-Experimental Procedure

After the data was collected, the data loggers were disconnected from the setup and reconnected to the computer. Using the CDLWin 4.0 software programme again, the data was downloaded from the loggers to the computer and initially evaluated in the programme. This was done by examining the graphical representation of the data against time. The data was then exported to Microsoft Excel. The full experimental procedure was now complete and all the data captured was saved to be analysed at a later stage. The pipe sample was removed from the setup and the setup is prepared for the next pipe sample.

3.4.4 Analysis of Data

For this section, the results of the uPVC Pilot Experiment, Class 9 with a drilled round hole of diameter 12mm, are used to explain of the data analysis procedure that was followed. The results for all the experimental runs are provided in Appendix B of this report.

3.4.4.1 Selecting Samples

Each pipe sample has two sets of data saved to Excel workbooks from the data loggers; one is pressure (bar) against time and the other is flow (l/s) against time. Graphical representations of these data sets were used to identify stable levels of flow and pressure. This was done by isolating each level in the step up and step down trend and finding the averages to generate a set of flow and pressure values. Figure 3.10 (a) and (b) show the raw data collected for flow vs time and pressure vs time. The graphs clearly show a step up and step down pattern that is repeated three times, and even though they are not identical, the flow and pressure values can easily be paired.

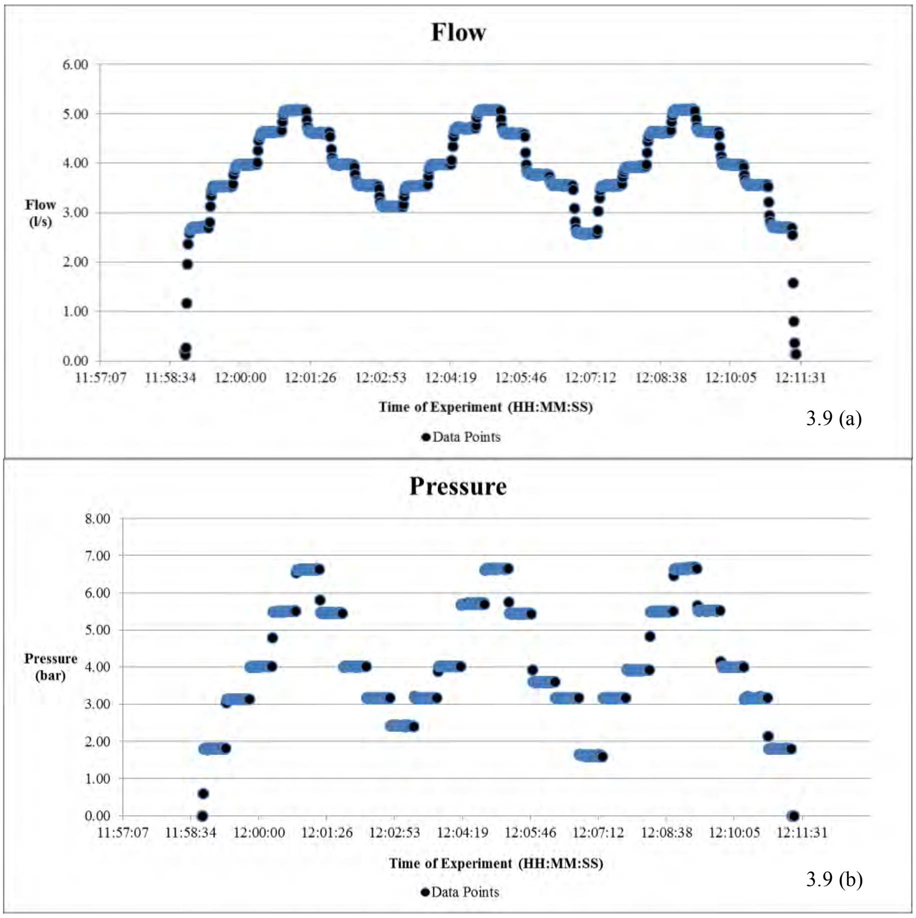

Figure 3.10: (a) flow vs time graph, **(b)** pressure vs time graph obtained from the uPVC (class 9) round hole leak, pilot experiment.

3.4.4.2 Interpretation of the Data

Once flow and pressure values have been determined from the raw data, they need to be converted to convenient units for analysis. Pressure is converted from bar to metres of head. The flow values first have the correction factor (given by equation 20 in section 3.3.2) applied to them before changing from litres per second (l/s) to cubic metres per second (m^3/s). Table 3.3 shows the primary experimental data i.e. the raw data collected as well as the final flow and head values determined for the analysis. Note that in the experimental templates provided in the Appendices, the flow correction factor column (data logger flow) is hidden.

Table 3.3: Primary Experimental Data (collected raw data and conversion to units required for the equations) for the uPVC round hole leak pilot experiment.

Sample	Data Logger Flow (l/s)	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)
1	2.70	1.30	1.81	1.30×10^{-03}	18.42
2	3.53	1.70	3.14	1.70×10^{-03}	32.01
3	3.97	1.92	4.02	1.92×10^{-03}	40.93
4	4.63	2.25	5.50	2.25×10^{-03}	56.02
5	5.07	2.47	6.63	2.47×10^{-03}	67.62
6	4.61	2.24	5.45	2.24×10^{-03}	55.57
7	3.98	1.93	4.02	1.93×10^{-03}	40.97
8	3.55	1.71	3.18	1.71×10^{-03}	32.42
9	3.13	1.50	2.42	1.50×10^{-03}	24.70
10	3.54	1.71	3.18	1.71×10^{-03}	32.39
11	3.97	1.92	4.02	1.92×10^{-03}	40.98
12	4.71	2.29	5.705	2.29×10^{-03}	58.15
13	5.08	2.47	6.66	2.47×10^{-03}	67.84
14	4.60	2.24	5.43	2.24×10^{-03}	55.40
15	3.77	1.82	3.60	1.82×10^{-03}	36.65
16	3.55	1.72	3.18	1.72×10^{-03}	32.42
17	2.58	1.23	1.61	1.23×10^{-03}	16.46
18	3.55	1.71	3.18	1.71×10^{-03}	32.42
19	3.92	1.90	3.91	1.90×10^{-03}	39.89
20	4.62	2.25	5.49	2.25×10^{-03}	55.97
21	5.08	2.48	6.66	2.48×10^{-03}	67.88
22	4.63	2.25	5.52	2.25×10^{-03}	56.24
23	3.97	1.92	4.00	1.92×10^{-03}	40.81
24	3.56	1.72	3.18	1.72×10^{-03}	32.43
25	2.70	1.29	1.80	1.29×10^{-03}	18.37

The flow and head values are then plotted on a graph and fitted with a power function. Figure 3.11 shows the flow vs head graph for the collected data:

The power equation (equation 2) is used to determine the Leakage Coefficient (*C*) and Leakage Exponent (*N1*) which are 3.05×10^{-04} and 0.50, respectively.

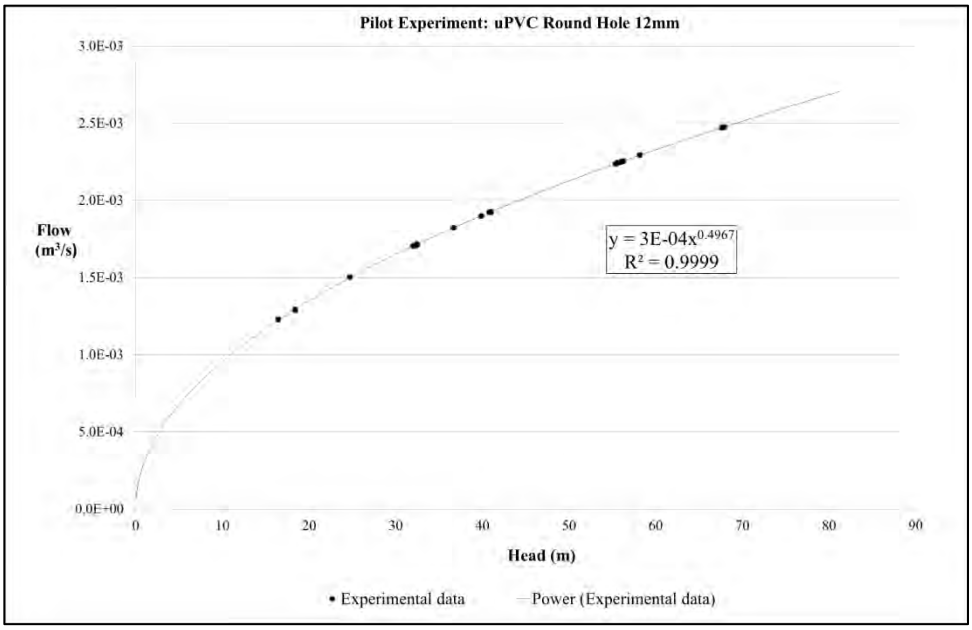

Figure 3.11: Flow vs. head graph with power function for the uPVC round hole Leak pilot experiment.

From equation 1 an expression for the effective area is developed:

$$C_d A = \frac{Q}{\sqrt{2gh^{0.5}}} \tag{21}$$

A graph for C_dA against head is then plotted and a linear function fitted to the sample points. Figure 3.12 shows the C_dA vs. head graph for the above set of data. The intercept of this graph is at C_dA_0 ($6.8 \times 10^{-0.5}$ m^2), and since A_0 (1.131×10^{-04} m^2) is known (calculated physically from the pipe sample), the Coefficient of Discharge (C_d) can be determined directly, in this case C_d is 0.6029. The linear function also shows that the slope (C_dm) is -5.477×10^{-09} m.

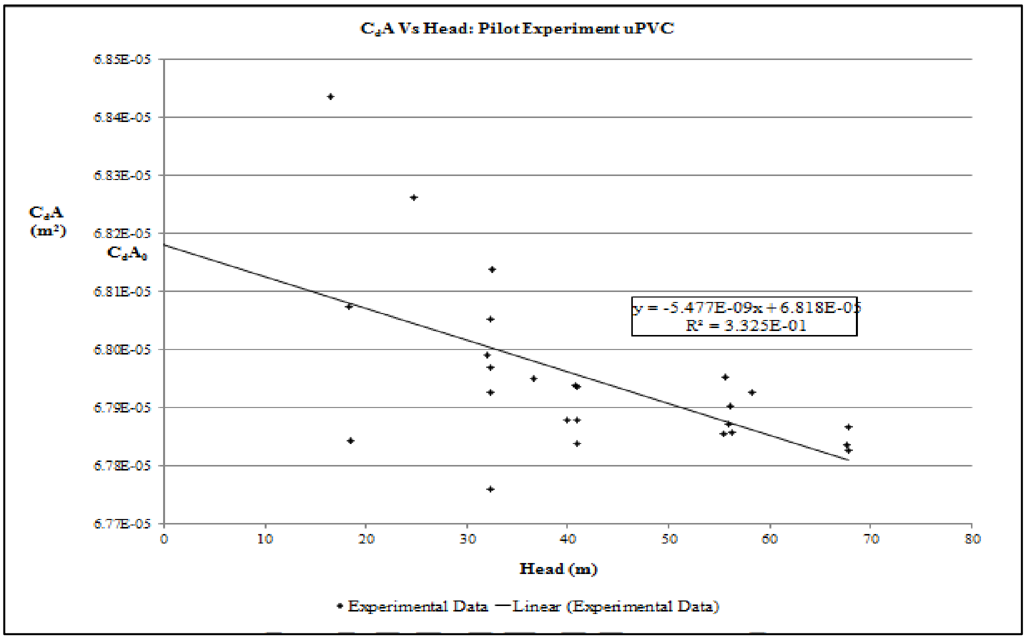

Figure 3.12: C_dA vs. head graph for the uPVC round hole leak pilot experiment.

Area (A) values are determined by dividing the C_dA values by C_d. The areas are plotted against the experimental head values to acquire the slope (m) for the head-area graph. Table 3.4 shows the C_dA and A values used; these are considered as the secondary experimental data points, and they are paired with their respective primary flow and head values.

Table 3.4: C_dA and A values determined using flow and head values for the uPVC round hole leak pilot experiment.

Sample	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)
1	1.2899E-03	18.4241	6.7844E-05	1.1254E-04
2	1.7038E-03	32.0082	6.7990E-05	1.1278E-04
3	1.9237E-03	40.9349	6.7879E-05	1.1260E-04
4	2.2512E-03	56.0216	6.7903E-05	1.1264E-04
5	2.4709E-03	67.6228	6.7837E-05	1.1253E-04
6	2.2438E-03	55.5701	6.7953E-05	1.1272E-04
7	1.9262E-03	40.9716	6.7937E-05	1.1269E-04
8	1.7141E-03	32.4159	6.7970E-05	1.1275E-04
9	1.5026E-03	24.6968	6.8263E-05	1.1323E-04
10	1.7083E-03	32.3948	6.7759E-05	1.1240E-04
11	1.9235E-03	40.9786	6.7837E-05	1.1253E-04
12	2.2944E-03	58.1532	6.7926E-05	1.1267E-04
13	2.4745E-03	67.8407	6.7825E-05	1.1251E-04
14	2.2370E-03	55.3954	6.7855E-05	1.1256E-04
15	1.8222E-03	36.6536	6.7951E-05	1.1272E-04

16	1.7162E-03	32.4159	6.8052E-05	1.1288E-04
17	1.2297E-03	16.4575	6.8435E-05	1.1352E-04
18	1.7131E-03	32.4159	6.7927E-05	1.1268E-04
19	1.8989E-03	39.8889	6.7879E-05	1.1260E-04
20	2.2492E-03	55.9706	6.7873E-05	1.1259E-04
21	2.4766E-03	67.8758	6.7866E-05	1.1257E-04
22	2.2541E-03	56.2410	6.7857E-05	1.1256E-04
23	1.9224E-03	40.8099	6.7938E-05	1.1269E-04
24	1.7188E-03	32.4300	6.8139E-05	1.1303E-04
25	1.2924E-03	18.3705	6.8074E-05	1.1292E-04

Figure 3.13 shows the head area graph for the above data. The graph shows how the area of the leak changes with increasing pressure. The linear function show's that the intercept A_0 is 1.131 x 10^{-04} m^2 which is the same as the physically calculated round hole (12mm diameter) area. This serves as a check to ensure that the mathematical procedure used is correct. Therefore the intercept A_0 value should be the same as the physically determined leak area for any leak shape and size. The head area slope here is determined to be -9.09 x 10^{-09} m.

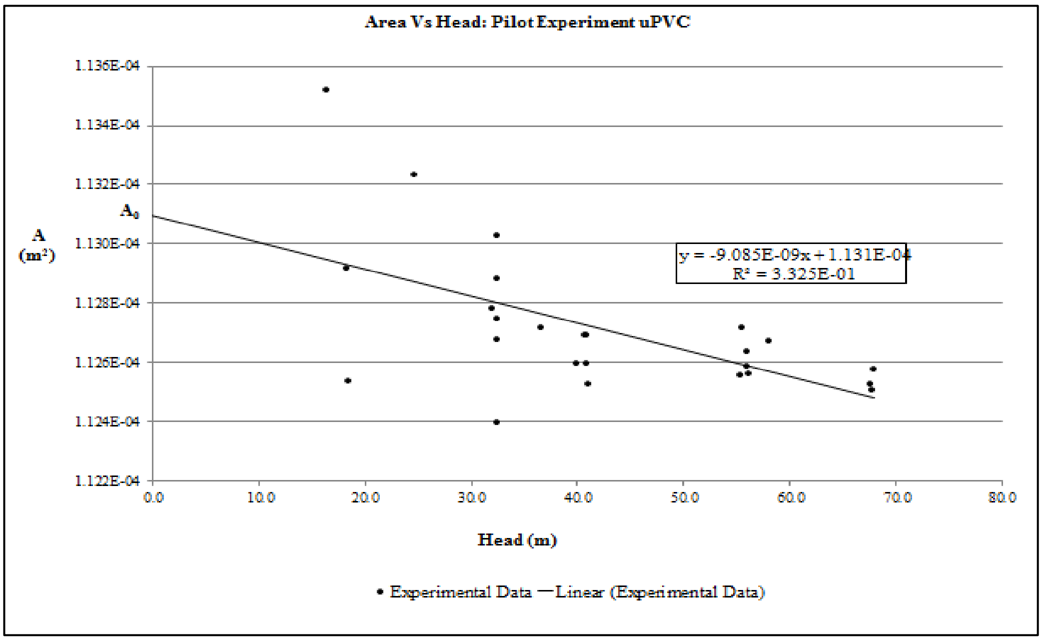

Figure 3.13: Area vs head graph used to determine head-area slope for the uPVC round hole leak pilot experiment.

From the experimental data, the parameters C, N1, C_d and m were calculated as demonstrated above. This process can be applied to any pipe material and any leak type. The parameters can now be used to compare the experimental data to the N1 and FAVAD equations. The N1 equation is given by equation 2 in section 2.2 of this report. The FAVAD equation is given by equation 14 in section 2.3 of this report.

C and N1 are substituted into the N1 equation and flow values are calculated for the experimental head values. The same is done with C_d and m values are being substituted into the FAVAD equation to determine a FAVAD flow value for each experimental head value.

Table 3.5 shows the tertiary experimental data (N1 and FAVAD flows) alongside their respective primary experimental flow and head values:

Table 3.5: N1 and FAVAD flow values calculated using the determined parameters (C, C_d, m, N1) with the experimental head values for the uPVC round hole leak pilot experiment.

Sample	Flow (m^3/s)	Pressure head (m)	N1 Flow (m^3/s)	FAVAD Flow (m^3/s)
1	1.2899E-03	18.4241	1.2951E-03	1.2944E-03
2	1.7038E-03	32.0082	1.7039E-03	1.7042E-03
3	1.9237E-03	40.9349	1.9253E-03	1.9259E-03
4	2.2512E-03	56.0216	2.2499E-03	2.2503E-03
5	2.4709E-03	67.6228	2.4704E-03	2.4700E-03
6	2.2438E-03	55.5701	2.2409E-03	2.2413E-03
7	1.9262E-03	40.9716	1.9261E-03	1.9267E-03
8	1.7141E-03	32.4159	1.7146E-03	1.7150E-03
9	1.5026E-03	24.6968	1.4980E-03	1.4979E-03
10	1.7083E-03	32.3948	1.7141E-03	1.7144E-03
11	1.9235E-03	40.9786	1.9263E-03	1.9269E-03
12	2.2944E-03	58.1532	2.2921E-03	2.2923E-03
13	2.4745E-03	67.8407	2.4743E-03	2.4739E-03
14	2.2370E-03	55.3954	2.2374E-03	2.2378E-03
15	1.8222E-03	36.6536	1.8225E-03	1.8230E-03
16	1.7162E-03	32.4159	1.7146E-03	1.7150E-03
17	1.2297E-03	16.4575	1.2245E-03	1.2236E-03
18	1.7131E-03	32.4159	1.7146E-03	1.7150E-03
19	1.8989E-03	39.8889	1.9007E-03	1.9013E-03
20	2.2492E-03	55.9706	2.2489E-03	2.2493E-03

21	2.4766E-03	67.8758	2.4750E-03	2.4746E-03
22	2.2541E-03	56.2410	2.2543E-03	2.2546E-03
23	1.9224E-03	40.8099	1.9224E-03	1.9230E-03
24	1.7188E-03	32.4300	1.7150E-03	1.7154E-03
25	1.2924E-03	18.3705	1.2932E-03	1.2925E-03

Now a comparison can be made between the experimental flow values and the N1 and FAVAD flow values. A simple but efficient way of comparing sets of data is by to use two statistical measures, Coefficient of Correlation (R^2) and the Sum of Squared Errors of Prediction (SSE).

The R^2 value shows how close the data points are fitted to the regression line. R^2 ranges between 0 - 100%, where 0% means that the model does not explain the variability of the data and 100% means the model fully explains the variability of the data. In general, the higher the R^2 value, the better the model fits the data. In this case the data would be the experimental data and the model would be the FAVAD and N1 equations.

The SSE is defined as the sum of squares of residuals. It is used as a measure of variation between an estimation model and data. A smaller SSE value indicates a smaller random error component and therefore a better fit between the model and the data.

Comparing the N1 flows to the experimental flows gives an N1 R^2 value and an N1 SSE value. Similarly, comparing the FAVAD flows to the experimental flows gives a FAVAD R^2 value and a FAVAD SSE value. These are presented in Table 3.6 alongside the respective N1 and FAVAD parameters.

Table 3.6: N1 and FAVAD parameters with their respective R^2 and SSE values for the uPVC round hole leak pilot experiment.

N_1 PARAMETERS	
C =	3.047E-04
N1 =	0.4967
R^2 =	0.99995
SSE =	0.0001906
FAVAD PARAMETERS	
C_dA_0 =	6.818E-05 m^2
C_d=	0.6029
m =	-9.085E-09
R^2 =	0.99995
SSE =	0.0001906

For the purpose of a visual comparison of the experimental results (Appendix D), the flow vs head graphs (such as Figure 3.11) are also fitted with the N1 and FAVAD equations across a head range of 0 - 100m alongside the experimental data points. Therefore in Appendix D the flow vs head graph will be presented as seen in Figure 3.14.

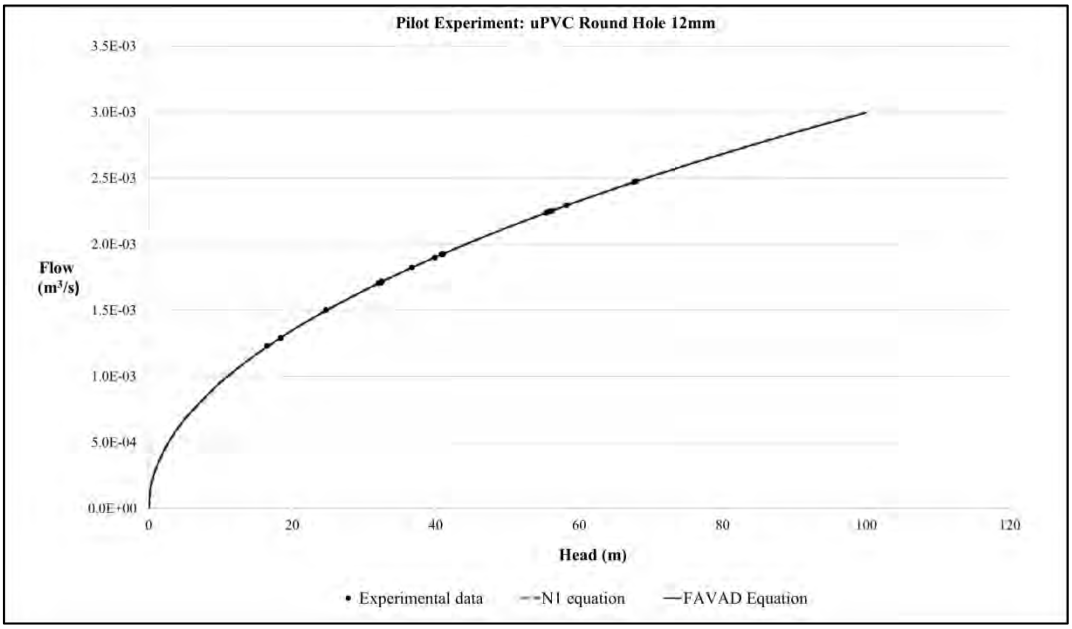

Figure 3.14: Layout for final flow vs. head graph used to present experimental results, which includes the experimental data, N1 equation and FAVAD equation.

3.5 Testing the Experimental Procedure and Data Analysis Method

This section discusses the verification experiments used to test the experimental procedure for competence, accuracy and efficiency.

3.5.1 Repeatability Analysis

The purpose of a repeatability analysis is to check that the experimental procedure produces consistent results for the same pipe sample. A large variation in the results for the same pipe sample would prove inefficiency in the experimental procedure.

The analysis is done by repeating the experiment from start to finish five times (five runs) with the same pipe sample, and including disconnecting and reconnecting the pipe sample at the start of each new run. The only difference is that the step up and step down method was done only once instead of repeating it three times consecutively, as mentioned in section 3.4.2 and shown by Figure 3.10 (a) and (b). The reason is that the data will not be analysed in as much detail as described in section 3.4.4.2.

Instead, the aim of this repeatability analysis is only to check the consistency of the maximum flow and pressure readings collected by the experimental setup. The secondary aim is to check consistencies for N1 and C between each of the five runs. If these results are consistent then that also shows that no experimental errors were incurred when replacing pipe samples.

The repeatability analysis was carried out on two pipes, uPVC class 9 and steel. Both pipe samples were 800 mm in length with an outer diameter of 110 mm and a round hole of 12 mm diameter drilled in the middle.

3.5.2 Discussion of Repeatability Analysis Results

The experiments were consistent with both the steel and the uPVC pipes getting very similar leakage exponents. Tables 3.7 and 3.8 summarise the results from the steel and uPVC repeatability experiments. The full repeatability analysis results are provided in Appendix B of this report.

Table 3.7: Summary of results from steel round hole 12mm repeatability analysis.

Run	Max. Flow (m^3/s)	Max. Head (m)	Leakage Coefficient (C)	Leakage Exponent (N1)
1	2.448×10^{-03}	68.453	2.992×10^{-04}	0.4974
2	2.451×10^{-03}	68.581	3.020×10^{-04}	0.4949
3	2.447×10^{-03}	68.660	3.012×10^{-04}	0.4955
4	2.450×10^{-03}	68.606	2.981×10^{-04}	0.4982
5	2.451×10^{-03}	68.701	2.991×10^{-04}	0.4974

Table 3.8: Summary of results from uPVC round hole 12mm repeatability analysis.

Run	Max. Flow (m^3/s)	Max. Head (m)	Leakage Coefficient (C)	Leakage Exponent (N1)
1	2.465×10^{-03}	67.411	3.017×10^{-04}	0.4987
2	2.473×10^{-03}	67.593	3.028×10^{-04}	0.4979
3	2.473×10^{-03}	67.540	3.001×10^{-04}	0.5005
4	2.472×10^{-03}	67.653	3.009×10^{-04}	0.4994
5	2.472×10^{-03}	68.681	2.995×10^{-04}	0.5006

The repeatability analysis results for the steel pipe show consistency. The maximum flow rates are all approximately 2.45×10^{-03} m^3/s. C and N are also consistent with values of 3.0×10^{-04} and 0.50 respectively. The maximum head varies slightly more but is consistent at approximately 68.5 m. A problem occurred when carrying out the first run in that the data logger connected to the flow meter ran out of battery, not allowing the final flow reading to be taken. For this reason, in the repeatability results in Appendix B, the first run has only 8 instead of 9 data points. This however, has not affected the results.

The repeatability analysis results for the uPVC pipe also show consistency. The maximum flow rates are all approximately 2.47 x 10^{-03} m^3/s. C and N1 are also consistent with values of 3.0 x 10^{-04} and 0.50 respectively. The maximum head varies slightly more but is consistent at approximately 67.5 m.

For both pipe samples the C and N1 values are consistent. However, the uPVC pipe sample has a slightly higher flow and slightly lower head value. This is expected because uPVC is more elastic than steel which means that at maximum internal pressure, the round hole will expand more in the uPVC than the steel.

The results also show that the N1 values can be determined to two decimal places. This is 0.50 for all the repeatability runs apart from run 2 of the steel experiment, which is 0.49. For this reason the accuracy of the results are ±0.01.

3.5.3 Pilot Experiments

The focus of these experiments is to check whether the loading and re-loading of the pipe sample, with internal pressures, brings about any inconsistencies caused by either visco-elastic or plastic behaviour of the pipe material, as well as whether consistent values are attained from the different experiments. The experimental procedure is similar to that of the repeatability experiments with the exception that the step up and step down method would be repeated three times in sequence and only one run was done as opposed to five.

When using the step-up and step down method three times consecutively, the pipe needs to be loaded, unloaded and then re loaded with internal pressure. When unloading the pipe sample (i.e. stepping down) the material takes time to relax to return to its original unstressed state. This means that the leak opening may not return to its original area before the pressure is increased again, which could bring about some discrepancies due to the inconsistent areas.

These experiments also used the same pipe samples as the repeatability experiments, uPVC class 9 and a steel pipe sample with a circular leak opening of 12mm diameter. The steel pipe sample does not deform visco-elastically because of its robust material properties. Therefore the steel sample is used as a benchmark to determine whether the uPVC pipe sample undergoes viscoelastic deformation.

For an increasing leak area, if the areas are noticeably higher each time the pipe is reloaded with internal pressure, this could be a sign of visco-elastic deformation since the leak area has not managed to return to its original size before increasing internal pressure. The opposite is true for a decreasing leak area, where the leak area should be at its largest when the head is lowest.

It should be noted that visco-elastic deformation is a complex behavioural pattern that is not fully understood and there is a lack of literature that discusses visco-elastic deformation of plastic pipes.

3.5.4 Discussion of Pilot Experiment Results

The full pilot experiment results are provided in Appendix B of this report. Figure 3.15 (a) and (b) show the Area vs Sample number of the uPVC and steel pilot experiments. Each sample number has a duration of 30 seconds, i.e. sample one is 0-30 seconds, sample two is 30-60 seconds, and so on. Using the step up and step down method three times consecutively gives three peaks and two valleys. The areas as the lowest head and therefore at the two valleys will be analysed. Sample numbers 9 and 17 represent the two valley heads and areas.

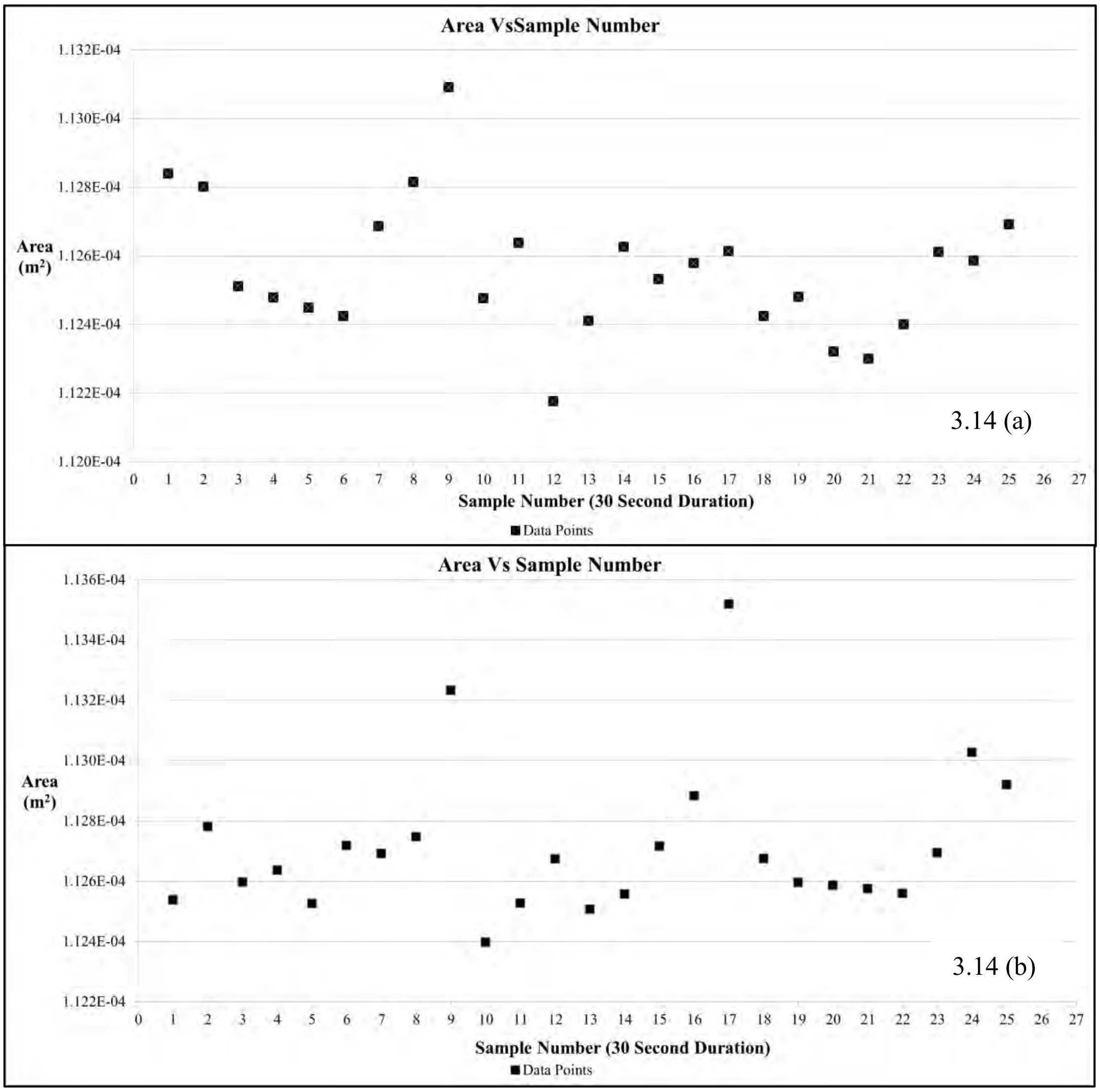

Figure 3.15: (a) Steel area vs. aample number graph, **(b)** uPVC area vs. sample number graph obtained from pilot experiment results.

Table 3.9 shows the lowest head values at each of the valleys during the step up and down procedure with the corresponding area. The steel sample has a slightly lower head in the first valley than the second valley. The uPVC has aslightly lower head in the second valley compared to the first. The steel has a slightly lower area in the second valley where as the uPVC has a slightly lower area in the first valley.

Table 3.9: Low head values and respective areas for the pilot experiments.

Pipe Material	H_9 (m)	A_9 (m^2)	H_{17} (m)	A_{17} (m^2)
Steel	32.431	1.131×10^{-04}	32.623	1.261×10^{-04}
uPVC	24.697	1.132×10^{-04}	16.458	1.135×10^{-04}

Both the steel and the uPVC pipe samples attained a N1 value of slightly less than 0.50 which means that there is a slight decrease in the leak area with increasing pressure. Table 3.10 shows that this is true as both the steel and the uPVC samples have slightly smaller areas at larger pressures. The steel sample does not deform visco-elasticlally and this shows a pattern for non visco-elastic behaviour. Since the uPVC behaves similarly to the steel pipe there is no evidence of viscoelastic deformation.

Plastic deformation was checked by measuring the diameter of the hole, across the longitudinal, circumferential and spiral axes. This was done before and after the experiment, using a Vernier Calliper. There are no signs of plastic deformation for both the steel and the uPVC samples, as the diameter lengths are the same in all cases as seen in Table 3.10. The circumferential crack length is longer than the longitudinal and spiral crack lengths due to the circumference of the pipe.

Table 3.10: Checking for change in hole diameter before and after experiment.

Pipe Sample	Longitudinal Diameter (mm)	Circumferential Diameter (mm)	Spiral Diameter (mm)
Steel before Experiment	12.00	12.05	12.00
Steel after Experiment	12.00	12.05	12.00
uPVC before experiment	12.00	12.05	12.00
uPVC after experiment	12.00	12.05	12.00

3.5.5 Sensitivity Analysis

As mentioned in section 3.4.1, when connecting the pipe sample, the leak orifice needs to be in line with the pressure transducer. This is to avoid any variation in head values. However, perfectly lining up the leak orifice with the pressure transducer is sometimes difficult as this is done by eye and it is very easy for the leak orifice to be offset by a few millimetres. The purpose of this analysis is to check whether not having the pressure transducer and leak orifice on the same line will affect the head values and if so, by how much.

Only one pipe sample was used for this analysis, namely steel with a round hole of 12mm diameter. The steel pipe was rotated about the axis and the experiment carried out at five locations about the horizontal axis, at 0°, 45°, 90°, 135°, 180°. Since the sensitivity experiment at 90° to the vertical axis has the orifice at the same location as the steel pilot experiment, the steel pilot experiment will be used for comparison as the 90° sensitivity experiment. To try and improve the accuracy the number of steps to the maximum head was increased from 5 to 6. This gives a total of 31 steps instead of 25 as in the previous experiments. The steel pilot results used as the 90° angle, however, will still use 25 steps.

Figure 3.16 shows a drawing of the pipe samples and the different locations used for testing. Comparisons were made are between the determined leakage exponents (N1) and the maximum head values achieved, at each testing level.

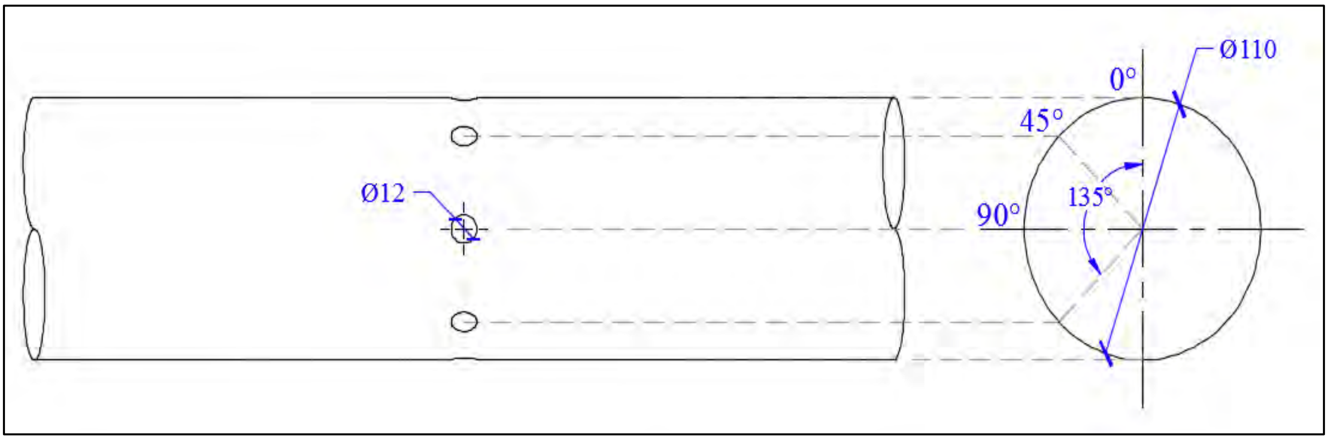

Figure 3.16: Location of circular orifice for sensitivity analysis.

3.5.6 Discussion of Sensitivity Results

The aim of this experiment was to check whether having the pressure transducer and the leak orifice on different longitudinal axes will affect the results due to the difference in head. For the purpose of this experiment the minimum head values and the leak area at these values were used for comparison, similar to the pilot experiment above. The reason is that the errors are more likely to be visible at lower pressures and that the leak area is a sensitive parameter. However, the area at the low head levels will also be compared the leak area calculated from the orifice equation (equation 1). The equivalent flow at the lowest head is used, the C_d of the respective run and g is used as 9.81 m/s^2.

The N1, C_d, C and m values have been separately compared to check the sensitivity of these parameters as well.

Table 3.11 shows the minimum head values and corresponding areas. Areas at the same pressure levels have been calculated using the orifice as presented in the table for comparison.

Table 3.11: Minimum head values with corresponding area and orifice calculated area for sensitivity analysis experiment.

Orifice Angle	Min Head 1 (m)	Area 1 (m^2) x 10^{-04}	Orifice Equation Area 1 (m^2) x 10^{-04}	Min Head 2 (m)	Area 2 (m^2) x 10^{-04}	Orifice Equation Area 1 (m^2) x 10^{-04}
0°	32.9150	1.1285	1.1286	32.9853	1.1275	1.1276
45°	32.8940	1.1295	1.1294	32.9432	1.1282	1.1281
90°	32.4305	1.1309	1.1309	32.6266	1.1261	1.1261
135°	32.9010	1.1302	1.1303	32.9713	1.1289	1.1291
180°	32.8869	1.1286	1.1286	32.9596	1.1282	1.1273

There is no pattern shown by the lowest head level and the angle of the orifice. The areas calculated by the orifice equation are identical to the areas determined experimentally to two decimal places with 1.13 x 10^{-04}. This proves that the angle of the orifice has no effect on the head and leak area in this experimental setup.

Table 3.12 shows the leakage parameters for each run. The C_d values are all 0.60 to two decimals places, the C values are 3.0 x 10^{-04} to one decimal place and the exponents are all 0.50 to tow decimal places apart from the 90° sample. The 90° sample also has the largest m values. The reason for the slight differences in the 90° sample as compared to the other samples is due to the increase in steps from 25 to 31. Since a larger amount of data points improves the accuracy of results it is clear that increasing the steps, which was the only difference between each of the runs, gave a slightly different result. However, the results show that the parameters are not very sensitive and experimental errors only come into effect when looking at 3 or more decimals places are considered.

Table 3.12: Leakage parameters for each run of the sensitivity analysis.

Orifice Angle	C_d	C	N1	M (m)
0°	0.5964	3.017 x 10^{-04}	0.4965	-8.410 x 10^{-09}
45°	0.5973	3.025 x 10^{-04}	0.4964	-6.881 x 10^{-09}
90°	0.5949	3.026 x 10^{-04}	0.4948	-1.129 x 10^{-08}
135°	0.5948	2.996x 10^{-04}	0.4982	-5.024 x 10^{-09}
180°	0.5962	3.010 x 10^{-04}	0.4972	-7.098 x 10^{-09}

The results of the sensitivity analysis show that not having the leak orifice on the exact horizontal line of the pressure transducer will not affect the readings. However, since the pipe sample used is 110mm, the maximum expected difference in head would be ± 55mm. This result may be negligible when using the high pressures and a small pipe diameter, but it could be more evident when using lower pressures and larger pipe diameters, as the expected difference in head would be larger.

3.6 New Experimental Procedure and Data Analysis Method

Based on the findings of the repeatability, pilot and sensitivity analyses, the following changes were made to the experimental procedure and analysis.

Since there was no visible evidence of visco-elastic or plastic deformation from the unloading and re-loading, as seen in the pilot experiments, the experiments used a maximum of three consecutive runs for time purposes. The duration of the steps will be left at 30 seconds; however, the amount of steps will be increased from 5 to 6 as done in the sensitivity analysis to improve accuracy by increasing sample points. This is the maximum amount of steps possible using the pump's VSD, and without either the flow or pressure values having too small an incremental increase.

The other change that had to be made is with the process of selecting samples (section 3.4.4.1). It is a time consuming and tedious process if done manually and therefore a simple Python programme was developed to select the samples straight from the raw data.

The design sheet and an example output file is provided in Appendix C of this report. In summary, the process used by the programme calculates the standard deviation between each point. When the pressure/flow levels are consistent the standard deviations are low between points. When the pressure/flow is increased or decreased, the standard deviation increases between the points. The programme notices these increases (approximately every 30 seconds) and isolates all the consistent small standard deviations, before finding an average value for the consistent values. Sometimes the increase or decrease is too small, then the programme will acquire average values over 60 or 90 seconds as opposed to 30 seconds. In this situation a scale factor can be applied to reduce the standard deviation jump which the programme is looking for. If the scale factor still does not bring down the steps to 30 seconds then the values will need to be found manually as before.

Apart from the above mentioned changes, the experimental procedure and analysis methods used continued to be those mentioned in section 3.4 of this chapter.

3.7 Pipe Samples Used for Testing

The final experimental procedure and data analysis were carried out on a series of pipe samples of different material and crack types. The results and discussion are provided in Chapter 4 of this report. Table 3.13 shows the details of each pipe sample used for testing. Note that all pipe samples have an outer diameter of 110mm and a length of 800mm. In the case of longitudinal, circumferential and spiral leak openings, the widths are 1mm.

Table 3.13: Pipe sample and respective details used for testing.

Pipe #	Material	Wall Thickness (mm)	Crack Type	Crack Dimension (mm)	Crack Area (mm^2)
01	mPVC	3.44	Round Hole	12	113.10
02	mPVC	3.44	Circumferential	50	50.00
03	mPVC	3.44	Longitudinal	50	50.00
04	mPVC	3.44	Spiral	50	50.00
05	HDPE	6.38	Circumferential	54	54.00
06	HDPE	6.38	Circumferential	80	80.00
07	HDPE	6.38	Longitudinal	73	73.00
08	HDPE	6.38	Longitudinal	100	100.00
09	HDPE	6.38	Round Hole	12	113.10
10	HDPE	6.38	Spiral	50	50.00
11	HDPE	6.38	Spiral	78	78.00
12	Steel	4.92	Circumferential	53	53.00
13	Steel	4.92	Longitudinal	50	50.00
14	Steel	4.92	Longitudinal	100	100.00
15	Steel	4.92	Round Hole	12	113.10
16	Steel	4.92	Spiral	50	50.00
17	Steel	4.92	Spiral	105	105.00
18	uPVC	4.54	Circumferential	50	50.00
19	uPVC	4.54	Circumferential	100	100.00
20	uPVC	4.54	Longitudinal	50	50.00
21	uPVC	4.54	Longitudinal	100	100.00
22	uPVC	4.54	Round Hole	12	113.10
23	uPVC	4.54	Spiral	50	50.00
24	uPVC	4.54	Spiral	100	100.00

Most cracks were made using Water Jet Technology (WJT). This method fires a jet of water with a fine abrasive material at a high velocity at the material that needs to be cut. Only pipes 18 and 21 were done by hand. Cutting of pipes by hand is a difficult and time consuming process. WJT will cut through most materials (metals, stones, plastics) but the smallest possible width is 1mm. Due to the circumference of the pipe sample, the width ranges from 0.9-1.1 mm, since the height of the water jet nozzle is fixed in place. The other challenge is cutting thin pipe materials; if the pipe is not turned at the right time, over exposure of the water jet could cause damage to the opposite side of the pipe.

3.8 Omitted Values

Some of the experiments discussed above consisted of flow and head values that were far from the mean of the collected data. These outliers have been omitted from the results presented above. This section will discuss the reasons for omitting these values. It should be noted that in Appendix D both the results from the original experiments and omitted experiments are provided, but the final results discussed in this report are of the omitted experiments. In total there were twelve experiments that had values omitted from them.

3.8.1 Settling-in Points

The majority of the omitted values were due to settling-in points. These are present in all HDPE pipes, apart from the HDPE round hole, and the mPVC longitudinal 50mm, mPVC spiral 50mm and uPVC longitudinal 50mm cracks (i.e. exp.03, 04, 05, 06, 07, 08, 10, 11, 20).

Figure 3.17 shows the original graph of flow vs. head of the mPVC longitudinal 50mm sample. The graph shows a set of 6 points that are distant from the mean of the collected data. These 6 points correspond to the first 6 flow and head readings (i.e. during the initial step up).

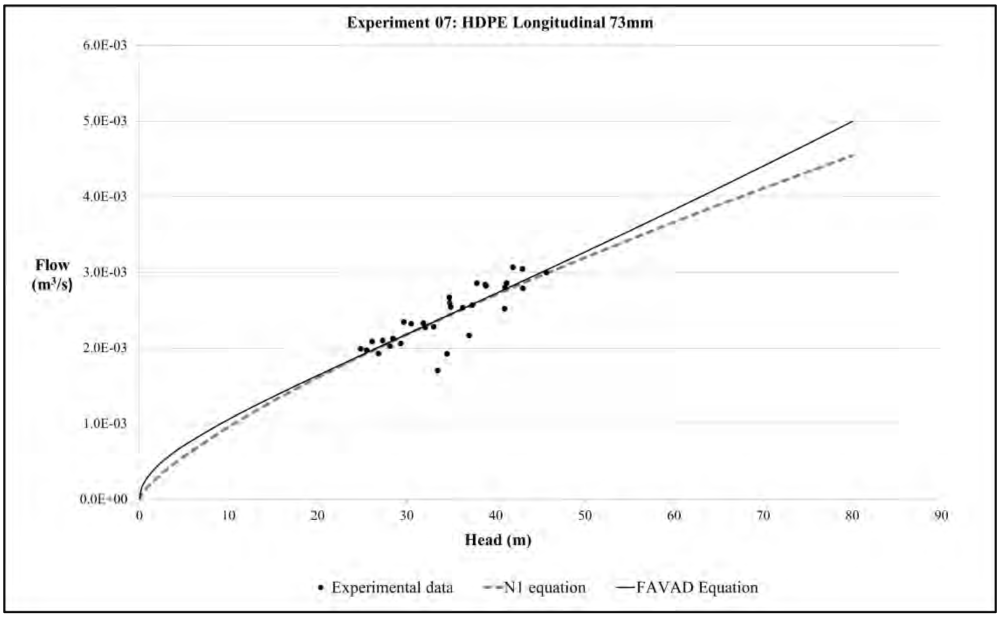

Figure 3.17: Flow vs. head graph for HDPE longitudinal 73mm sample which shows settling in points.

Since only the first six steps are the outliers, this is evidence that the pipe material has not settled in or stabilised yet. Once the maximum pressure head is reached, the material stabilises and the rest of the readings are consistent.

The material behaves in this manner because of the artificially induced leak. The pipe sample was not subject to such high pressures when the leaks were created and therefore requires some time to stabilise.

It is also clear that since all but one HDPE pipe has settling-in points, the more elastic the material the higher the chance of the material needing to stabilise before data can be collected. The HDPE round hole did not have settling-in points because circular shaped leaks have proven to be very stable in terms of deformation.

The mPVC longitudinal 50mm, spiral 50mm and uPVC longitudinal 50mm samples also had settling in points. mPVC and uPVC are less elastic than HDPE but still have a high elasticity. Therefore having a few of the mPVC and uPVC samples with settling-in points is not un expected.

The steel pipes did not have the same settling in points as the plastic because of its rigidity. However, there were signs of the sample needing to settle in; this will be discussed in section 4.5.2.

To confirm that omitting these 6 initial settling-in points improves the accuracy of the data model, a comparison was made between two of the leakage parameters (N1 and m) and statistical indicators (R^2 and SSE) of the original experiment data and the omitted experiment data. The reason for only comparing the N1 and m of the leakage parameters is because they provide a simple interpretation of the behaviour of the leak. Table 3.14 shows the comparison between the original experiments and the omitted values experiments.

Table 3.14: Comparison of results between the original experimental data and the omitted experimental data for plastic samples with outliers.

Pipe Sample	N1	m	N1 R^2	N1 SSE	FAVAD R^2	FAVAD SSE
mPVC Longitudinal 50mm	0.9302	9.50×10^{-07}	0.7559	2.88×10^{-04}	0.7597	2.88×10^{-04}
mPVC Longitudinal 50mm (omitted)	0.9887	1.16×10^{-06}	0.9786	2.30×10^{-04}	0.9795	2.38×10^{-04}
mPVC Spiral 50mm	0.8106	4.53×10^{-07}	0.9837	2.34×10^{-04}	0.9841	2.40×10^{-04}
mPVC Spiral 50mm (omitted)	0.7983	4.32×10^{-07}	0.9967	1.90×10^{-04}	0.9973	1.94×10^{-04}
HDPE Circumferential 50mm	0.1789	-1.65×10^{-07}	0.2250	2.45×10^{-05}	0.2329	2.47×10^{-05}
HDPE Circumferential 50mm (omitted)	0.1850	-1.63×10^{-07}	0.4587	1.93×10^{-05}	0.4820	1.86×10^{-05}
HDPE Circumferential 75mm	-0.2878	-4.57×10^{-07}	0.1465	4.11×10^{-05}	0.1286	4.85×10^{-05}
HDPE Circumferential 75mm (omitted)	-0.2623	-4.43×10^{-07}	0.2511	2.90×10^{-05}	0.2752	3.27×10^{-05}
HDPE Longitudinal 75mm	0.7488	7.74×10^{-07}	0.6959	3.49×10^{-04}	0.6996	3.72×10^{-04}
HDPE Longitudinal 75mm (omitted)	0.8355	1.13×10^{-06}	0.9345	2.85×10^{-04}	0.9356	3.04×10^{-04}
HDPE Longitudinal 100mm	0.7296	1.54×10^{-06}	0.7834	4.54×10^{-04}	0.7864	4.68×10^{-04}

HDPE Longitudinal 100mm (omitted)	0.7985	2.15×10^{-06}	0.9616	3.64×10^{-07}	0.9628	3.79×10^{-04}
HDPE Spiral 50mm	0.6956	1.744×10^{-07}	0.8273	1.16×10^{-04}	0.8275	1.29×10^{-04}
HDPE Spiral 50mm (omitted)	0.6563	1.42 x 10-07	0.9565	1.03×10^{-04}	0.9573	1.03 x 10-04
HDPE Spiral 75mm	0.6934	4.81×10^{-07}	0.8671	3.12×10^{-04}	0.8694	3.45×10^{-04}
HDPE Spiral 75mm (omitted)	0.7026	5.10×10^{-07}	0.9813	2.74×10^{-04}	0.9822	2.82×10^{-04}
uPVC Longitudinal 50mm	0.8859	5.24×10^{-07}	0.9828	1.54×10^{-04}	0.9840	1.58×10^{-04}
uPVC Longitudinal 50mm (omitted)	0.8691	4.90×10^{-07}	0.9958	1.27×10^{-04}	0.9968	1.28×10^{-04}

Table 3.15 shows that the N1 and FAVAD R^2 values are closer to one for the omitted experiments. Similarly, the N1 and FAVAD SSE are also lower. Omitting the outliers does not have a large effect on the N1 and m values but slightly improves the accuracy of the data. There are small changes with every N1 and m but the improvements can be seen mainly in the R^2 and SSE values, as some of the samples have considerable changes. One example is the R^2 value of 0.87 increasing to 0.98 for the HDPE spiral 75mm sample.

3.8.2 Other Outliers

There are three other experiments that have outliers amongst the data. These three experiments are all steel samples: the round hole 12mm, longitudinal 100mm and spiral 100mm sample.

For the steel round hole, the outlier was found to be the first flow and head value of the experiment. This means that the steel sample also needed some time to settle in but not as much time as the plastics. After the first point the pipe stabilises and therefore only the first point is omitted from the data.

The steel longitudinal sample had a similar problem but the first two data points were outliers instead of just the first. This is the same situation as for the steel round hole sample where the pipe needed to stabilise but did so in two steps. The ability of the steel sample to stabilise quickly has to do with the material's robustness but is also due to the deformations for the steel samples being very small.

The steel spiral 100mm sample had three outliers but they were not the initial data points. Instead these outliers were present at the peak of the last step up and step down (i.e. sample numbers 24, 25, 26). This is due to the localised stresses around the leak. When the leak was made, it was cut from outside inwards. Therefore, there is a small ridge that runs along the leak area on the inside if the leak. This is caused by the water jet pushing through the pipe wall. When the pipe is filled with water and there is discharge through the leak, the water has to run over the ridge before being expelled through the leak. A possibility is that during the step up and step down procedure, the ridge has fractured off the pipe and slightly blocked the leak area. This has resulted in the flow and pressure readings to fluctuate slightly.

Once again a comparison was made between the omitted and original experiments as done in section 4.5.1. Table 3.15 shows the results of the comparison. The results are also more accurate as can be seen by the R^2 values being closer to one and the SSE values being lower for every sample.

Table 3.15: Comparison of results between the original experimental data and the omitted experimental data for steel samples with outliers.

Pipe Sample	N1	m	N1 R^2	N1 SSE	FAVAD R^2	FAVAD SSE
Steel Round Hole 12mm	0.4929	-1.59×10^{-08}	0.9994	2.653×10^{-04}	0.9994	2.64×10^{-04}
Steel Round Hole 12mm (omitted)	0.4965	-8.15×10^{-09}	0.9999	2.58×10^{-04}	0.9999	2.58×10^{-04}
Steel longitudinal 100mm	0.5193	3.35×10^{-08}	0.9977	1.63×10^{-04}	0.9979	1.61×10^{-04}
Steel longitudinal 100mm (omitted)	0.5289	4.84×10^{-08}	0.9999	1.53×10^{-04}	0.9999	1.53×10^{-04}
Steel Spiral 100mm	0.5226	3.84×10^{-08}	0.9825	1.60×10^{-04}	0.9823	1.58×10^{-04}
Steel Spiral 100mm (omitted)	0.5184	3.20×10^{-08}	0.9998	1.36×10^{-04}	0.9998	1.37×10^{-04}

4 Results and Discussion

This chapter summarises the results of all the experiments done on the pipe samples described in section 3.7. The results are presented in the categories of leak shapes followed by their respective dimensions. Firstly the behaviour of round holes is discussed followed by that of longitudinal cracks, circumferential cracks and spiral cracks. After each leak type has been discussed individually, an overall discussion is presented in the final section of this chapter. All the experimental results presented in this chapter are provided in Appendix D of this report.

4.1 Round Holes

4.1.1 12mm Diameter

Four experiments (01, 09, 15, 22) were carried out on round holes with a diameter of 12mm. All four pipe materials were tested, i.e. mPVC, HDPE, steel and uPVC. Figure 4.1 shows the experimental data for all four materials.

All four materials follow a similar pattern. The HDPE sample has a slightly higher flow than the rest. The steel sample has a slightly lower flow than the rest. The mPVC and uPVC are very similar to each other. They are located in between the HDPE and steel but closer to the steel.

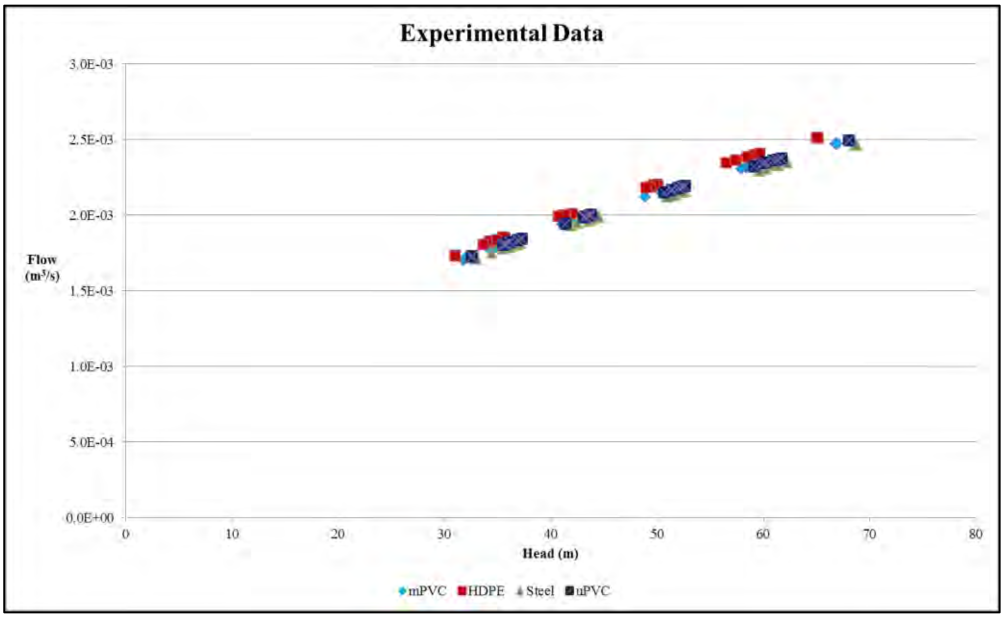

Figure 4.1: Experimental data for each pipe sample with a round hole leak of diameter 12mm.

Figure 4.2 shows the N1 and FAVAD equations for all four materials. The N1 and FAVAD are very similar to each other and fit almost directly on top of each other for all materials.

The equations follow a similar pattern to the experimental data, with HDPE having the highest flows and steel having the lowest flows. The mPVC equations cannot be seen as ithey are hidden behind the uPVC equation, showing their similarities.

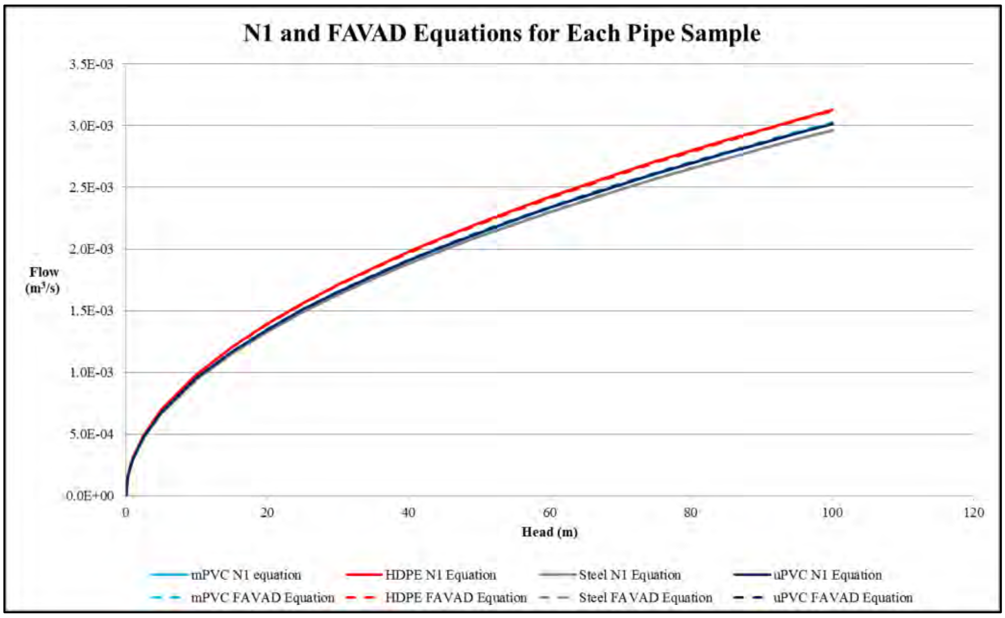

Figure 4.2: N1 and FAVAD equations for round hole leaks with a diameter of 12mm.

Figure 4.3 shows how the leak area varies with the pressure head for all four materials. The leak area changes differently for all materials, i.e. two materials expand and two contract. HDPE has the largest increase in area, followed by mPVC. The uPVC sample slightly decreased in leak area, and the steel sample had the largest decrease in area. It is clear that the A_0 of the steel does not line up with the A_0 values of the other materials. This has to do with the omitted values discussed in section 3.8. Some experiments which had omitted values have their linear trend lines offset by different amounts. This is possibly due to an error in Microsoft Excel and could not be rectified in time. However, further examination of the data showed that the leakage parameters are not affected by this offset. This is shown by the Area vs head equation (Experiment 15, omitted, Appendix D) which has an intercept identical to the other materials. For this reason, any offset A_0 values due to omitted results have been ignored. It should be noted that some A_0 values differ due to manufacturing processes which affects the leakage parameters.

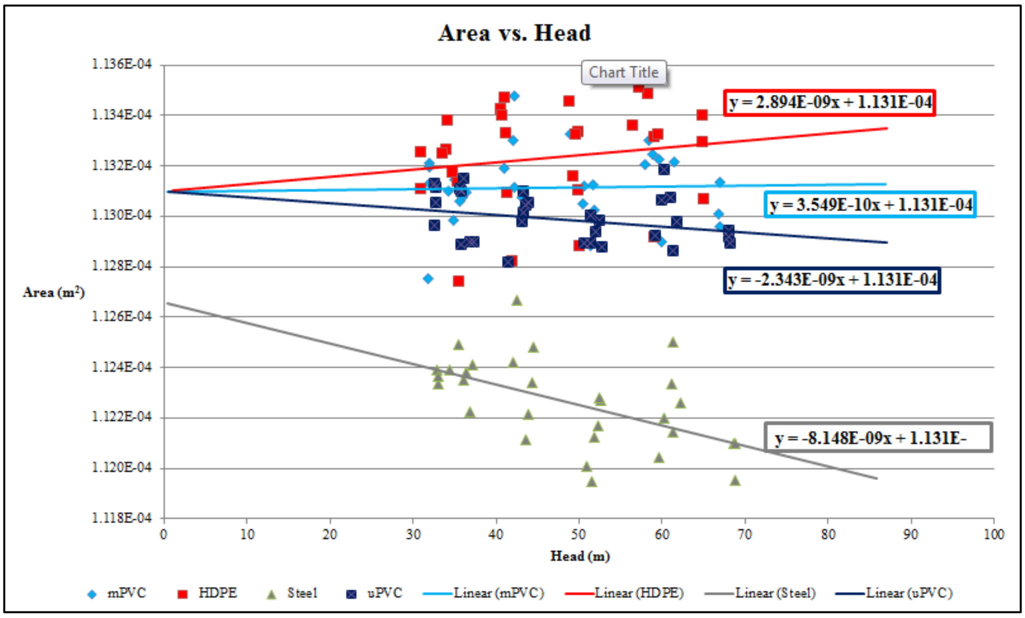

Figure 4.3: Leak area against head for round hole leaks with a diameter of 12mm.

Table 4.1 summarises the leakage parameters for all four materials tested. The C_d values determined were all close to 0.60, with HDPE being the highest with 0.6212, and steel being the lowest with 0.5960. The C values are also consistent at an expected 3.0 x 10^{-04}. However, the HDPE has a slightly higher C value at 3.1 X 10^{-04}. Even though there are slight differences with the N1 values, they are all 0.50 when rounded to two decimal places. The m values show that HDPE has the highest positive slope and steel has the highest negative slope.

Table 4.1: Summary of leakage parameters determined for a round hole leak with a diameter of 12mm.

Pipe Sample	C_d	C	N1	m (m)	A_0 (m^2)
mPVC	0.6039	3.022 x 10^{-04}	0.5003	3.549 x10^{-10}	1.131x10^{-04}
HDPE	0.6212	3.102 x 10^{-04}	0.5012	2.894 x10^{-09}	1.131x10^{-04}
Steel	0.5960	3.015 x 10^{-04}	0.4965	-8.148 x10^{-09}	1.131x10^{-04}
uPVC	0.6035	3.032 x 10^{-04}	0.4990	-2.343 x10^{-09}	1.131x10^{-04}

Table 4.2 compares the experimental data to the N1 and FAVAD equations. The experimental data has a very close correlation to the N1 and FAVAD equations. This is shown by the R^2 values being close to 1, which means that the fit almost fully explains the variation of the data. The low N1 and FAVAD SSE values with 2.7 x 10^{-04} for all materials also show a small random error component. The R^2 and SSE for all materials are close to the average values with minimal variation between the values.

Table 4.2: Statistical comparison of the N1 and FAVAD equations with the experimental data for a round hole leak with a diameter of 12mm.

Pipe Sample	R^2		SSE	
	N1	FAVAD	N1	FAVAD
mPVC	0.99990	0.99990	2.654×10^{-04}	2.664×10^{-04}
HDPE	0.99979	0.99979	2.712×10^{-04}	2.702×10^{-04}
Steel	0.99988	0.99988	2.580×10^{-04}	2.583×10^{-04}
uPVC	0.99996	0.99995	2.705×10^{-04}	2.708×10^{-04}
Average	**0.99988**	**0.99988**	$\mathbf{2.663 \times 10^{-04}}$	$\mathbf{2.664 \times 10^{-04}}$

4.1.2 Discussion

HDPE had the highest flows for the experimental data as well as the N1 and FAVAD equations. Steel had the lowest flows for the experimental data and the N1 and FAVAD equations. mPVC and uPVC followed similar trends as expected since they have very similar material properties apart from wall thickness which gives them different maximum operating pressure ratings (600kPa and 900kPa respectively).

The results show that round holes had very small expansions and contractions with low m values. The main significance is that some values were positive and some were negative.

For round hole leaks, the R^2 values are almost 100% for both the N1 and the FAVAD equations. The SSE values are similar and very low. This shows that both the N1 and the FAVAD equations are effective in predicting the behaviour of a circular leak with diameter 12mm.

4.2 Longitudinal Cracks

4.2.1 50mm

Three experiments (03, 13, 20) were carried out on longitudinal cracks with a length of 50mm and a width of 1mm. The three pipe materials tested were mPVC, steel and uPVC.

Figure 4.4 shows the experimental flows against head for all three materials. The mPVC sample has the highest flows and the steel has the lowest flows. The uPVC is located in between the mPVC and steel.

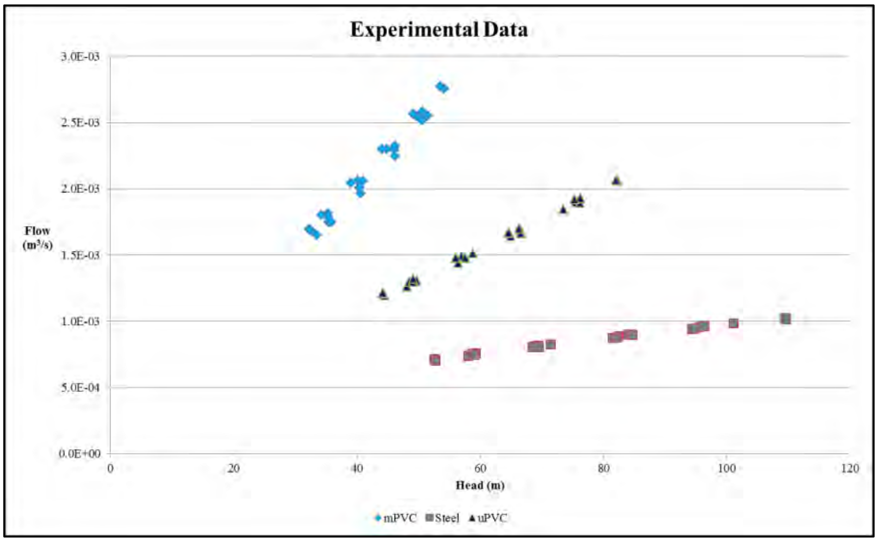

Figure 4.4: Experimental data for each pipe sample with a longitudinal crack of length 50mm and width 1mm.

Figure 4.5 shows the N1 and FAVAD equations for each of the longitudinal 50mm samples. The N1 and FAVAD data points have also been presented in this graph so that the similarities can be seen. However, because of congestion on the graph the N1 and FAVAD data points are not presented in the following figures.

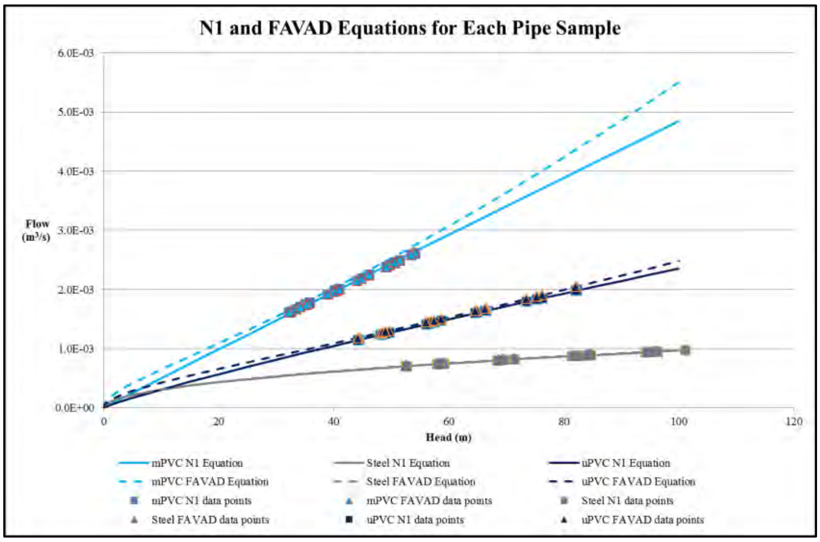

Figure 4.5: N1 and FAVAD equations and data points for longitudinal cracks with length 50mm and width 1mm.

In Figure 4.5, the equations follow a similar pattern to the experimental data with mPVC having the highest flows, followed by uPVC and then steel. However, the N1 and FAVAD equations show differences especially in the mPVC and the uPVC. The Steel FAVAD equation does seem to have slightly higher flows closer to 100m of head. The FAVAD equations for the mPVC and uPVC have higher flows than their respective N1 equations. The higher flows are not consistent as the mPVC FAVAD curve initially starts off with higher flows than the mPVC N1 curve but then starts to move closer to the N1 curve between 35 m to 45m of head. The FAVAD curve then starts to move away from the N1 equation as it approaches 100m of head. The uPVC FAVAD equation behaves in the same manner but has flows are lower than for the mPVC. This could be the same for the steel sample as well, but the differences are so small that they cannot be seen clearly in the graph.

Figure 4.6 shows how the area for each of the materials varies with pressure head. All the samples show an expansion. mPVC has the greatest expansion, followed by uPVC and lastly steel. The steel sample has a very small expansion, hence the low m value.

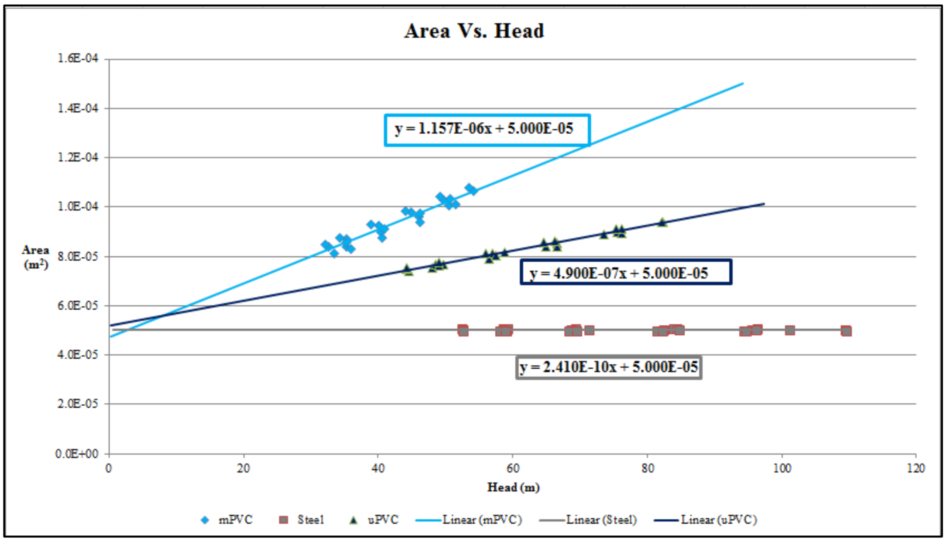

Figure 4.6: Leak area against head for longitudinal cracks of length 50mm and width 1mm.

Table 4.3 summarises the leakage parameters for longitudinal cracks with a length of 50mm. All the parameters vary for the different pipe materials. mPVC has the highest C_d value at 0.7492 and steel has the lowest at 0.4401. Steel has the highest C value at 9.74 x 10^{-05} whereas uPVC has the lowest C value at 4.42 x 10^{-05}. The mPVC has a very high N1 value of almost 1, followed by a high N1 value for uPVC at 0.87. Steel has the lowest N1 value at 0.50. The m values show that mPVC has the greatest expansion followed by uPVC and then steel.

Table 4.3: Summary of leakage parameters determined for longitudinal cracks with approximate crack length and width of 50mm and 1mm respectively.

Pipe Sample	C_d	C	N1	m (m)	A_0 (m^2)
mPVC	0.7492	5.284 x 10^{-05}	0.9887	1.157 x 10^{-06}	5.000 x 10^{-05}
Steel	0.4401	9.740 x 10^{-05}	0.5002	2.410 x 10^{-10}	5.000 x 10^{-05}
uPVC	0.5671	4.421 x 10^{-05}	0.8691	4.900 x 10^{-07}	5.000 x 10^{-05}

Table 4.4 compares the experimental data to the N1 and FAVAD equations. The average R^2 values for both the N1 and FAVAD equations are 99% which shows a good fit. The mPVC sample had the lowest fit at 98%, which is still a good fit. The average SSE values are very

low; especially the steel's SSE value which shows that it has the lowest random error component of the materials in this test.

Table 4.4: Statistical comparison of the N1 and FAVAD equations with the experimental data for a longitudinal crack of length 50mm and width 1mm.

Pipe Sample	R^2		SSE	
	N1	FAVAD	N1	FAVAD
mPVC	0.97857	0.97949	2.297×10^{-04}	2.377×10^{-04}
Steel	0.99750	0.99750	4.494×10^{-05}	4.538×10^{-05}
uPVC	0.99577	0.99683	1.265×10^{-04}	1.284×10^{-04}
Average	**0.99061**	**0.99127**	$\mathbf{1.337 \times 10^{-04}}$	$\mathbf{1.372 \times 10^{-04}}$

4.2.2 75mm

Only one experiment (07) was carried out on longitudinal cracks with a length of approximately 75mm and a width of 1mm. Note that the actual length of the crack is 73mm and this length was used in the calculations. The pipe material tested was HDPE.

Figure 4.7 shows the experimental data alongside the N1 and FAVAD equations. The N1 and FAVAD equations have a similar pattern to the longitudinal 50mm cracks where the FAVAD equation initially has higher flows but then comes closer to the N1 equation before moving away on approaching the 100m of head mark.

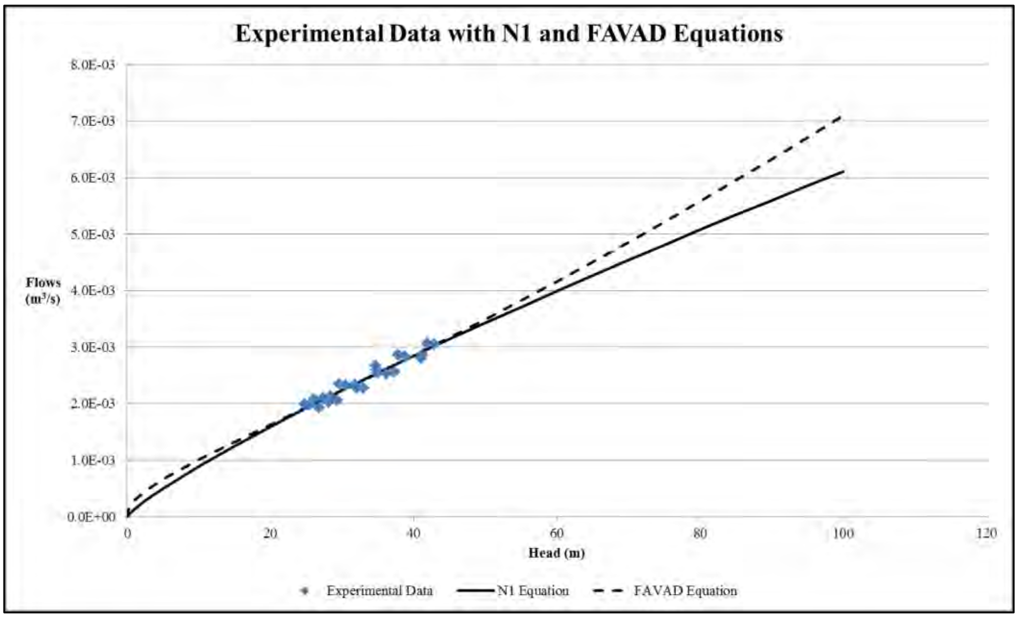

Figure 4.7: Experimental data with the N1 and FAVAD equations for HDPE with a longitudinal crack of length 75mm and width 1mm.

Figure 4.8 shows the change in area with head or the HDPE sample. The leak area expands with increasing pressure.

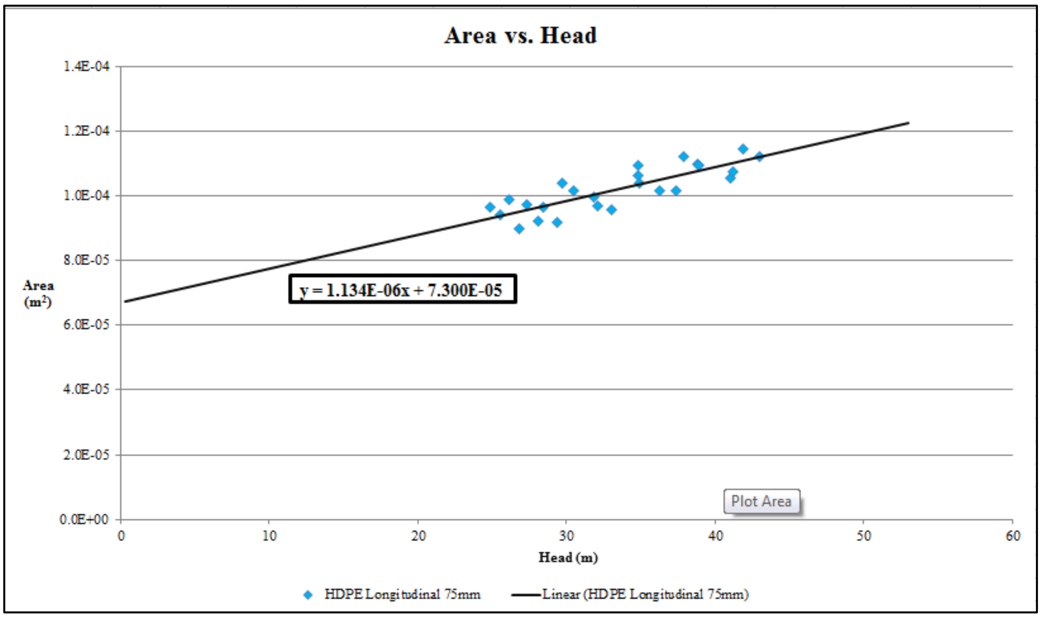

Figure 4.8: Area against head for HDPE with a longitudinal crack of length 75mm and width 1mm.

Table 4.5 summarises the leakage parameters for the HDPE sample. The C_d value is high at 0.8597. The C value is also high at 1.30 x 10^{-04}. There is a clear expansion shown by the N1 value of 0.84 and a positive m slope.

Table 4.5: Summary of leakage parameters determined for a longitudinal crack with crack length of 75mm and width of 1mm.

Pipe Sample	C_d	C	N1	m (m)	A_0 (m^2)
HDPE	0.8597	1.304 x 10^{-04}	0.8355	1.134 x 10^{-06}	7.300 x 10^{-05}

Table 4.6 compares the experimental data to the N1 and FAVAD equations of the HDPE sample. The R^2 values for both the N1 and FAVAD equations are above 90% with the FAVAD equation being slightly higher than the N1 equation. The SSE values are low, but in this case the N1 equation has a lower SSE value than the FAVAD equation.

Table 4.6: Statistical comparison of the N1 and FAVAD equations with the experimental data for a longitudinal crack of length 75mm and width 1mm.

Pipe Sample	R^2		SSE	
	N1	**FAVAD**	**N1**	**FAVAD**
HDPE	0.93448	0.93562	2.852×10^{-04}	3.040×10^{-04}
Average	0.93448	0.93562	2.852×10^{-04}	3.040×10^{-04}

4.2.3 100mm

Three experiments (08, 14, 21) were carried out on longitudinal cracks with a length of 10mm and a width of 1mm. The three pipe materials tested were HDPE, steel and uPVC.

Figure 4.9 shows the experimental data for all three materials. The HDPE sample has slightly higher flows than the uPVC sample. The steel has considerably lower flows but very high pressure values.

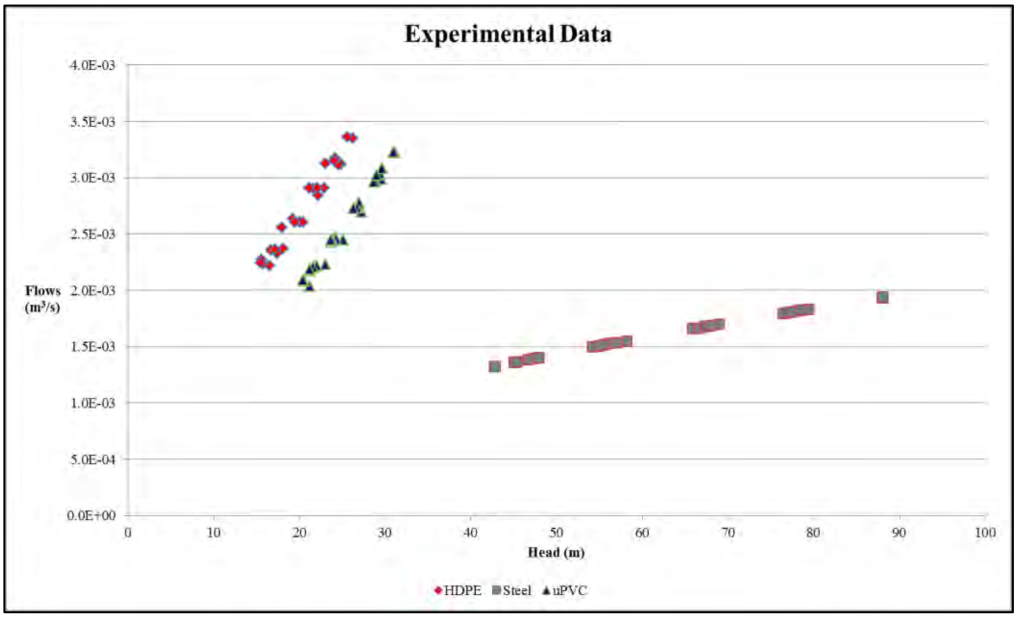

Figure 4.9: Experimental data for each pipe sample with a longitudinal crack of length 100mm and width 1mm.

Figure 4.10 shows the N1 and FAVAD equations for all the pipe samples. The steel N1 and FAVAD equations are identical. They follow a similar pattern to the experimental data and maintain low flows. The HDPE N1 equation starts off with higher flows than the uPVC N1 equation but then crosses below the N1 equation at almost 60m of pressure head. The FAVAD equations for the HDPE and uPVC have a similar behaviour to the longitudinal 50mm and 75mm samples with the exception of a larger variation. Both HDPE and uPVC

FAVAD equations clearly have higher flows closer to the 100m of head mark than the N1 equations.

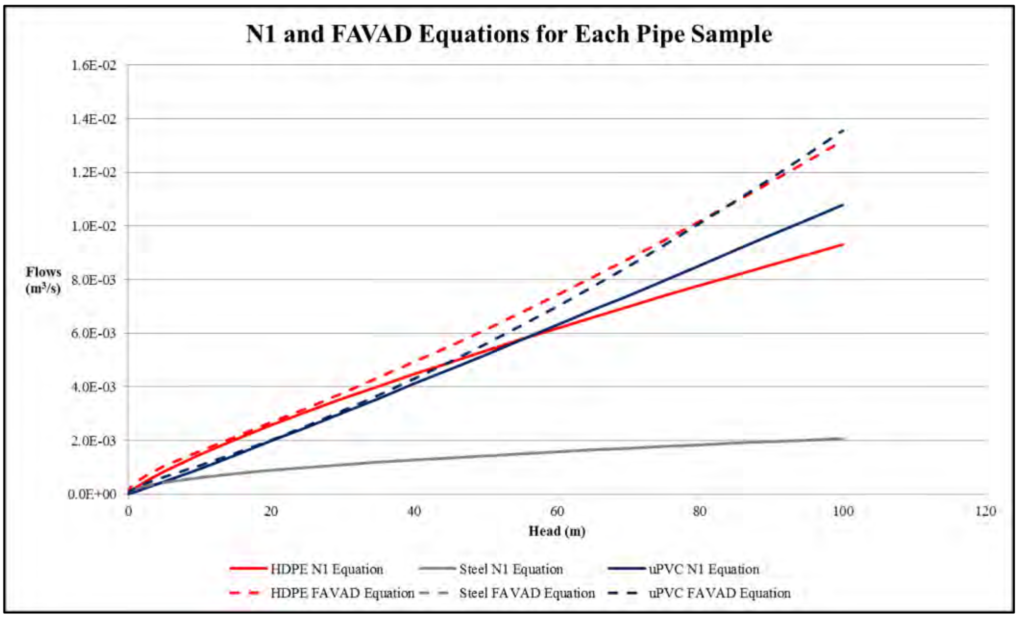

Figure 4.10: N1 and FAVAD equations for longitudinal cracks with length 100mm and width 1mm.

Figure 4.11 shows how the area varies with the pressure head for each of the samples. Here, uPVC has the greatest expansion, followed by HDPE and then steel which has a very gentle positive slope.

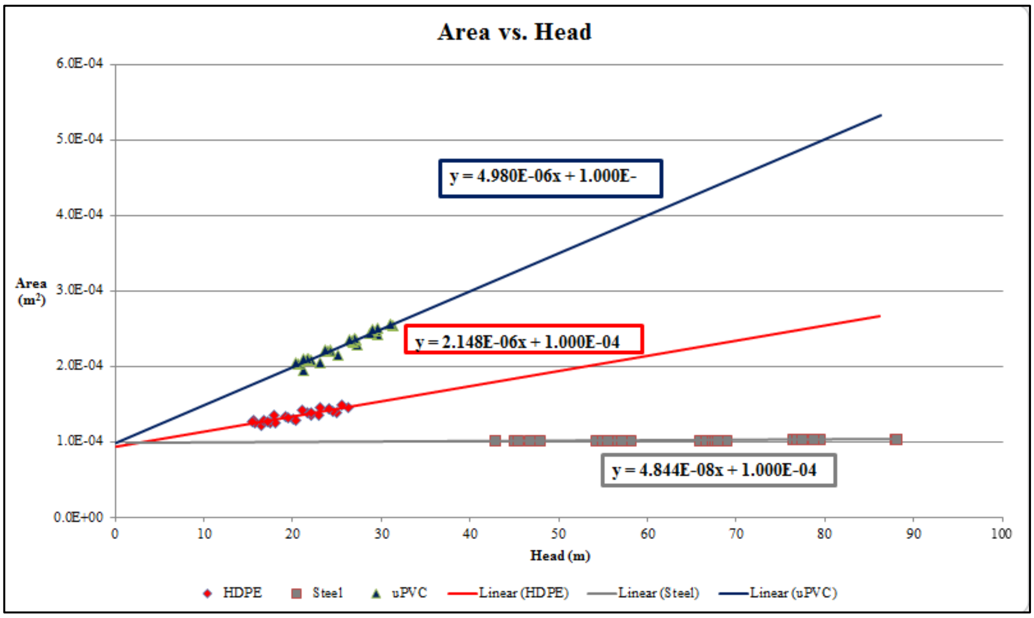

Figure 4.11: Leak area against head for longitudinal cracks of length 100mm and width 1mm.

Table 4.7 summarises the leakage parameters for longitudinal cracks with a length of 100mm. All the parameters vary for different pipe materials. HDPE has the highest C_d value at 0.9450 and steel has the lowest at 0.4471. HDPE also has the highest C value at 2.45 x 10^{-04} whereas uPVC has the lowest C value at 8.58 x 10^{-05}. The uPVC has a very high N1 value of greater than 1, followed by a high N1 value for HDPE at 0.80. Steel had the lowest N1 value at 0.53. The m values show that uPVC has the greatest expansion followed by HDPE and then steel.

Table 4.7: Summary of leakage parameters determined for longitudinal cracks with approximate crack length and width of 100mm and 1mm respectively.

Pipe Sample	C_d	C	N1	m (m)	A_0 (m^2)
HDPE	0.9450	2.454 x 10^{-04}	0.7985	2.148 x 10^{-06}	1.000 x 10^{-04}
Steel	0.4471	1.812 x 10^{-04}	0.5289	4.844 x 10^{-08}	1.000 x 10^{-04}
uPVC	0.5114	8.581 x 10^{-05}	1.0535	4.980 x 10^{-06}	1.000 x 10^{-04}

Table 4.8 compares the experimental data to the N1 and FAVAD equations. The average R^2 value for both the FAVAD and N1 equations were 98%, showing a good fit. The SSE values are low for all samples with steel once again having the lowest random error component

Table 4.8: Statistical comparison of the N1 and FAVAD equations with the experimental data for a longitudinal crack of length 50mm and width 1mm.

Pipe Sample	R^2		SSE	
	N1	FAVAD	N1	FAVAD
HDPE	0.96155	0.96284	3.640 x 10^{-04}	3.792 x 10^{-04}
Steel	0.99985	0.99990	1.533 x 10^{-04}	1.531 x 10^{-04}
uPVC	0.98519	0.98585	4.188 x 10^{-04}	4.260 x 10^{-04}
Average	**0.98220**	**0.98286**	**3.120 x 10^{-04}**	**3.194 x 10^{-04}**

4.2.4 Discussion

All the longitudinal cracks showed an expansion in area. The plastic materials (HDPE, mPVC and uPVC) all had large expansions which are due to their higher elasticity. The steel sample is stiffer and denser and therefore did not expand as much as the others. It is clear that the longer the longitudinal crack length the larger the expansion, which was shown by all materials.

Table 4.9 shows a comparison of the experimental data with the N1 and FAVAD equations for longitudinal cracks. The R^2 values for both N1 and FAVAD equations is 97%, showing a good fit, although the FAVAD R^2 is slightly higher than the N1 R^2. The SSE values for both the N1 and FAVAD equations are low, showing a small random error component, although the N1 SSE is slightly lower than the FAVAD SSE component.

Table 4.9: Statistical comparison of the N1 and FAVAD equations with the experimental data for longitudinal cracks.

Crack length	R^2		SSE	
	N1	FAVAD	N1	FAVAD
50mm	0.99061	0.99127	1.337×10^{-04}	1.372×10^{-04}
75mm	0.93448	0.93562	2.852×10^{-04}	3.040×10^{-04}
100mm	0.98220	0.98286	3.120×10^{-04}	3.194×10^{-04}
Average	**0.96910**	**0.96992**	$\mathbf{2.436 \times 10^{-04}}$	$\mathbf{2.535 \times 10^{-04}}$

4.3 Circumferential Cracks

4.3.1 50mm

Four experiments (02, 05, 12, 18) were carried out on circumferential cracks with an approximate length of 50mm and a width of 1mm. The four pipe materials were: mPVC, HDPE, steel and uPVC.

Figure 4.12 shows the experimental data for all samples. mPVC has the highest flows, closely followed by uPVC, then steel and lastly HDPE.

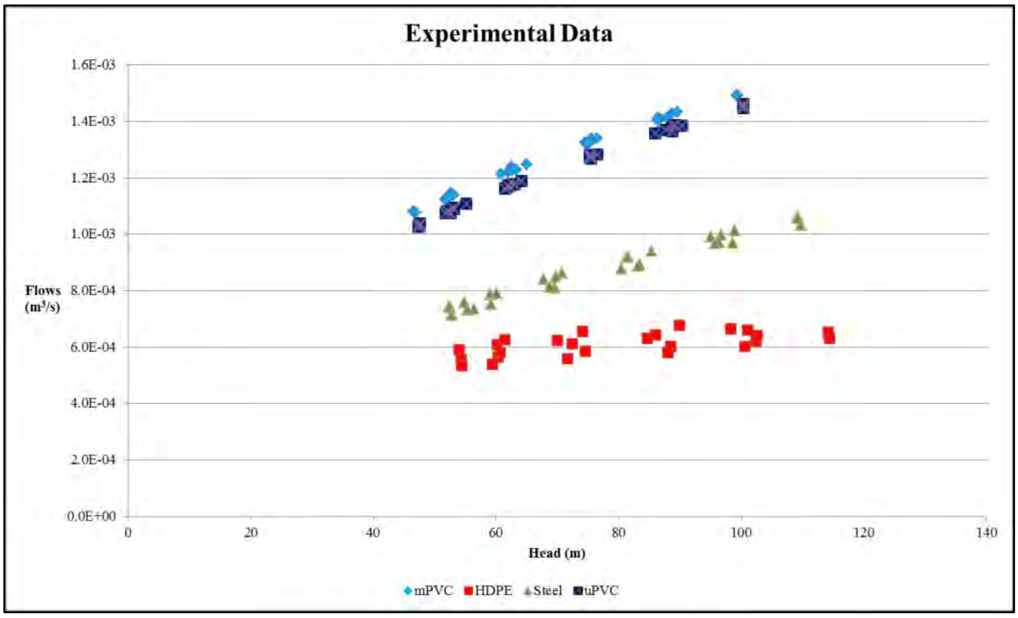

Figure 4.12: Experimental data for each pipe sample with a circumferential crack of length 50mm and width 1mm.

Figure 4.13 shows the N1 and FAVAD equations for each of the pipe samples. The mPVC, N1 and FAVAD equations are very similar to each other with a slight variation before 40 m and after 80 m of head. The uPVC N1 and FAVAD equations follow a similar pattern to those of the mPVC with slightly lower flows. The steel N1 and FAVAD equations start closer together but as the pressure increases; the FAVAD equation has slightly higher flows. The significant variation is with the HDPE sample. The HDPE N1 equation starts off with much higher flows than the FAVAD equation but they come closer together around the 80 m head mark after which the N1 equation again starts moving away from the FAVAD equation.

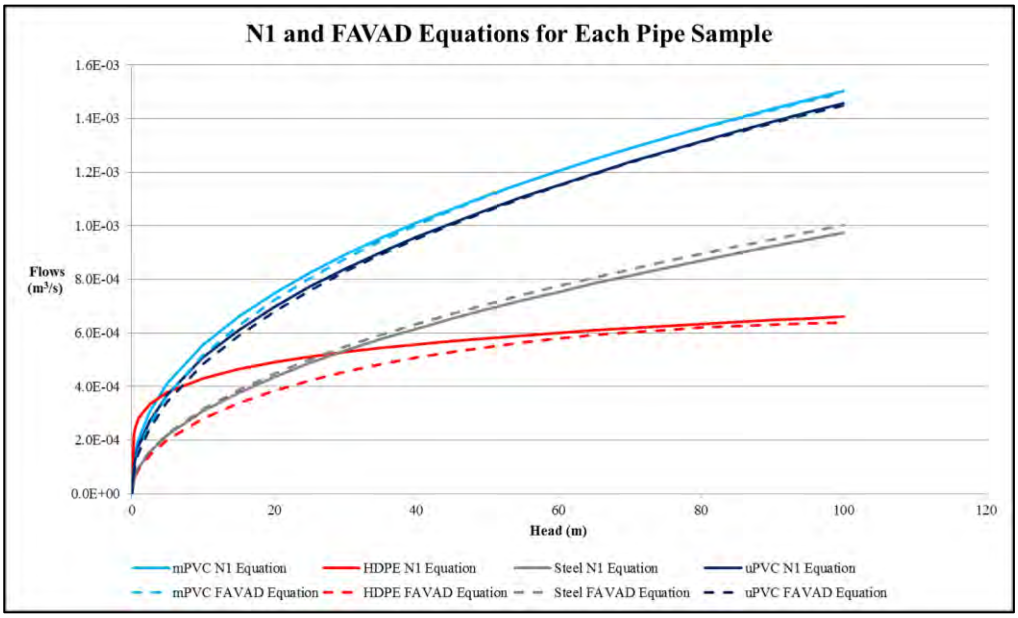

Figure 4.13: N1 and FAVAD equations for circumferential cracks with length 50mm and width 1mm.

Figure 4.14 shows how the area varies with the pressure head for each of the samples. All samples show a contraction of the leak area. HDPE has the greatest contraction, followed by mPVC, uPVC and then steel, which has a very gentle negative slope. Note that the A_0 values are slightly different for the HDPE and steel as shown in Table 4.9. This is due to an accidental error when inducing the leak with water jet technology.

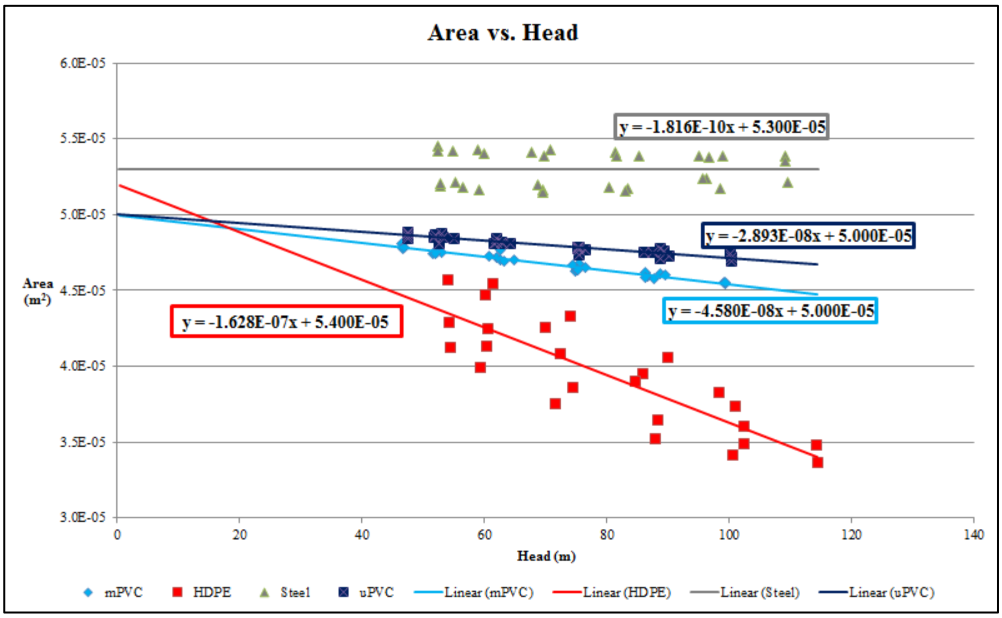

Figure 4.14: Leak area against head for circumferential cracks of length 50mm and width 1mm.

Table 4.10 summarises the leakage parameters for circumferential cracks with a length of 75mm. All the parameters vary for different pipe materials. HDPE has the lowest C_d value at 0.3815 and mPVC has the highest at 0.7431. HDPE also has the highest C value at 2.72 x 10^{-04} whereas steel has the lowest C value at 1.01 x 10^{-04}. The HDPE has a very low N1 value of 0.19. The uPVC and mPVC samples also showed signs of contraction with an N1 of 0.46 and 0.43. Steel had the highest N1 value at 0.49 which shows that it did contract, although by a very small amount. The m values show that HDPE had a much greater contraction than the other pipe samples. The steel pipe once again deformed the least due to its robust material properties.

Table 4.10: Summary of leakage parameters determined for circumferential cracks with approximate crack length and width of 50mm and 1m respectively.

Pipe Sample	C_d	C	N1	m (m)	A_0 (m)
mPVC	0.7431	2.045 x 10^{-04}	0.4328	-4.580 x 10^{-08}	5.000 x 10^{-05}
HDPE	0.3815	2.718 x 10^{-04}	0.1850	-1.628 x 10^{-07}	5.400 x 10^{-05}
Steel	0.4265	1.005 x 10^{-04}	0.4991	-1.816 x 10^{-10}	5.300 x 10^{-05}
uPVC	0.6945	1.764 x 10^{-04}	0.4578	-2.893 x 10^{-08}	5.000 x 10^{-05}

Table 4.11 compares the experimental data to the N1 and FAVAD equations. The R^2 values for the N1 and FAVAD equations had an average of 0.86032. This means that approximately 14% of the experimental data cannot be explained by the N1 and FAVAD equation. The SSE values however are significantly low, showing the lowest random error component thus far.

Table 4.11: Statistical comparison of the N1 and FAVAD equations with the experimental data for a circumferential crack of length 50mm and width 1mm.

Pipe Sample	R^2		SSE	
	N1	FAVAD	N1	FAVAD
mPVC	0.99854	0.99873	1.016×10^{-04}	1.014×10^{-04}
HDPE	0.45868	0.48198	1.928×10^{-05}	1.862×10^{-05}
Steel	0.97358	0.97358	4.632×10^{-05}	4.762×10^{-05}
uPVC	0.99876	0.99869	9.435×10^{-05}	9.404×10^{-05}
Average	**0.85739**	**0.86325**	$\mathbf{6.534 \times 10^{-05}}$	$\mathbf{6.542 \times 10^{-05}}$

4.3.2 75mm

Only one experiment (06) was carried out on circumferential cracks with a length of approximately 75mm and a width of 1mm. Note that the actual length of the crack is 80mm and this length was used in the calculations. The pipe material tested was HDPE.

Figure 4.15 shows the experimental data alongside the N1 and FAVAD equations. The experimental data maintained low flows with high pressure values. The N1 equation starts off high and decreases as the head increases. The FAVAD equation starts off low and increases with increasing pressure until approximately 50m of head when it starts to decline slowly with increasing pressure.

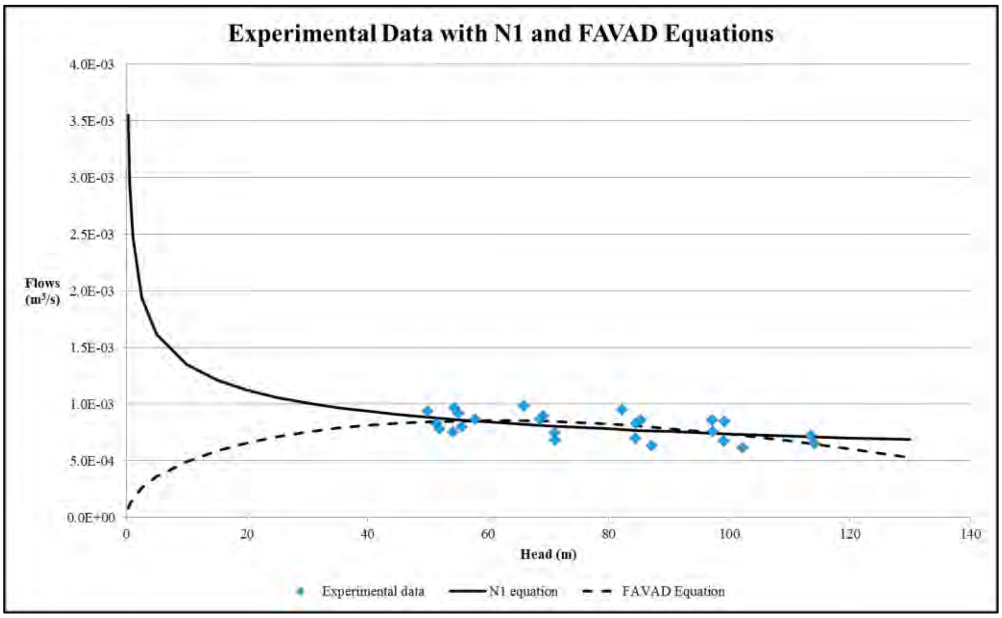

Figure 4.15: Experimental data with the N1 and FAVAD equations for HDPE with a circumferential crack of length 75mm and width 1mm.

Figure 4.16 shows the change in area with head for the HDPE sample. The area contracts with increasing pressure.

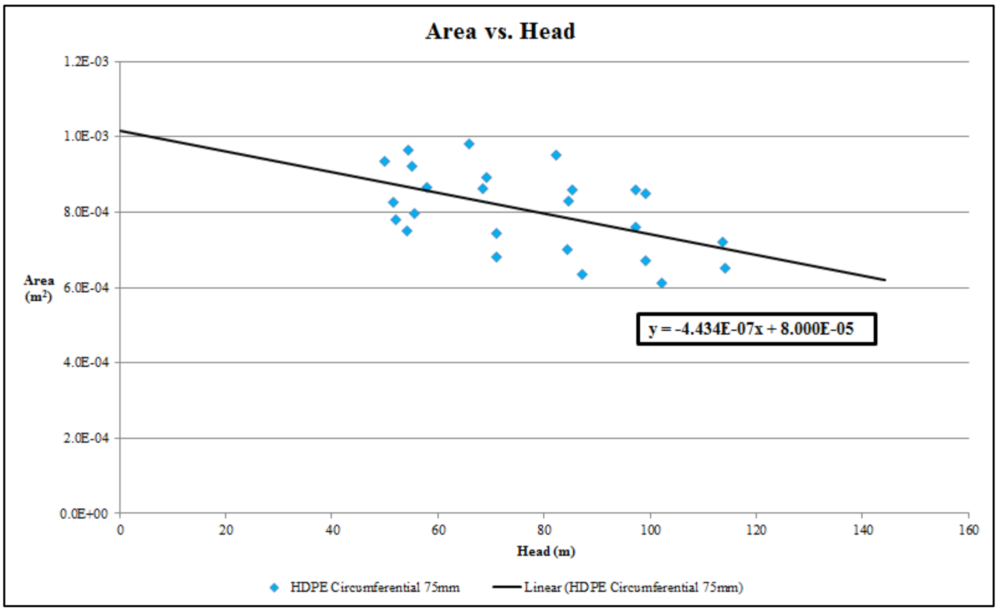

Figure 4.16: Area against head for HDPE with a circumferential crack of length 75mm and width 1mm.

Table 4.12 summarises the leakage parameters for the HDPE sample. The C_d value is 0.4670. The C value is high at 2.47 x 10^{-03}. The leakage exponent is -0.26. Negative leakage exponents are rarely encountered. They occur when the flows decrease over time. The m value is a large negative slope showing that the area is contracting rapidly.

Table 4.12: Summary of leakage parameters determined for a circumferential crack with crack length and width of 75mm and 1m respectively.

Pipe Sample	C_d	C	N1	m (m)	A_0 (m^2)
HDPE	0.4670	2.468 x 10^{-03}	-0.2623	-4.434 x 10^{-07}	8.000 x 10^{-05}

Table 4.13 compares the experimental data to the N1 and FAVAD equations of the HDPE sample. The R^2 values are very low for both the N1 and FAVAD equations with an average of 0.26311, which means that approximately 74% of the experimental data's variation is unexplained by the N1 and FAVAD equations. The low SSE values however show that both the N1 and FAVAD equations have small random error components although the N1 equation is slightly smaller than the FAVAD equations' SSE value.

Table 4.13: Statistical comparison of the N1 and FAVAD equations with the experimental data for a circumferential crack of length 75mm and width 1mm.

Pipe Sample	R^2		SSE	
	N1	**FAVAD**	**N1**	**FAVAD**
HDPE	0.25106	0.27516	2.900×10^{-05}	3.271×10^{-05}
Average	**0.25106**	**0.27516**	$\mathbf{2.900 \times 10^{-05}}$	$\mathbf{3.271 \times 10^{-05}}$

4.3.3 100mm

Only one experiment (19) was carried out on circumferential cracks with a length of a 100mm and a width of 1mm. The pipe material tested was uPVC.

Figure 4.17 shows the experimental flows alongside the N1 and FAVAD equations for the uPVC sample. The N1 equation starts off with a steeper increase in flow compared to the FAVAD equation but then starts to move towards the FAVAD equation although it never touches it. The FAVAD equation fits the experimental data better than the N1 equation.

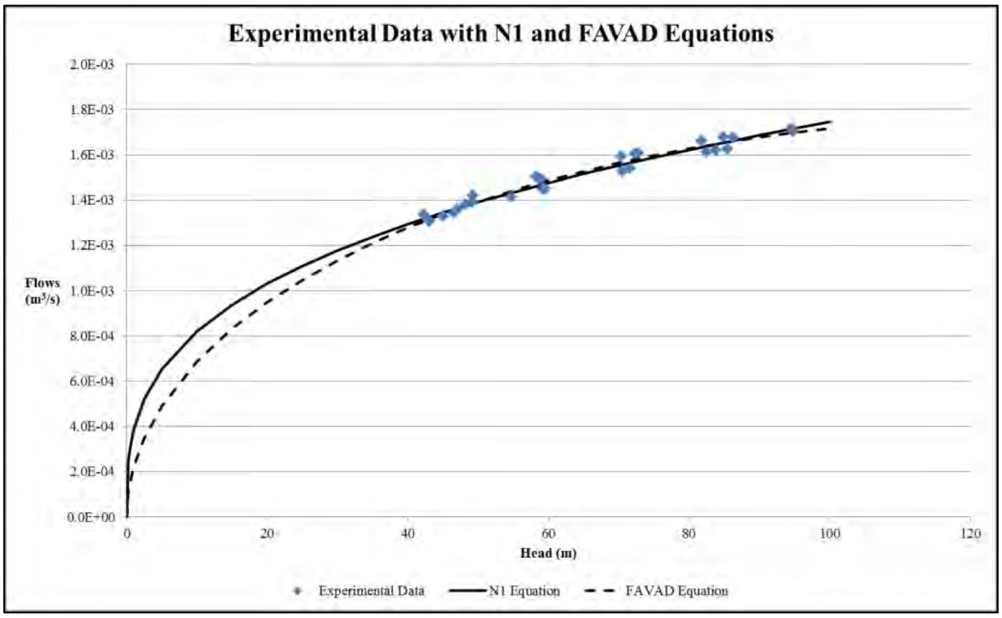

Figure 4.17: Experimental data with the N1 and FAVAD equations for uPVC with a circumferential crack of length 100mm and width 1mm.

Figure 4.18 shows the change in area with the head for the uPVC sample. The area contracts with increasing head.

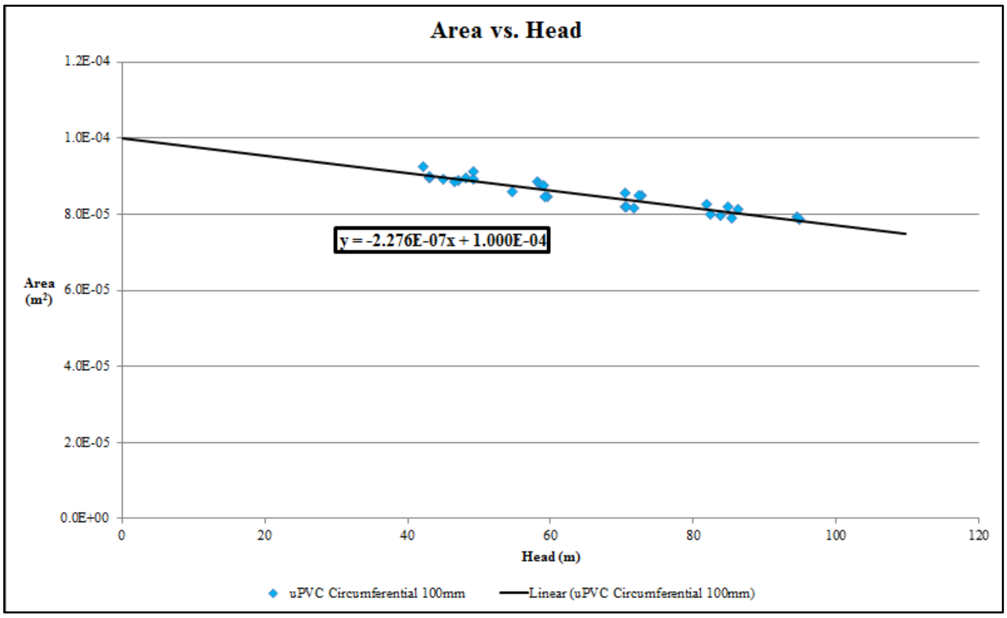

Figure 4.18: Area against head for uPVC with a circumferential crack of length 100mm and width 1mm.

Table 4.14 summarises the leakage parameters for the uPVC sample. The C_d value is 0.5019. The C value is 3.87 x 10^{-04}. The leakage exponent is 0.32. The m value shows a negative steep slope.

Table 4.14: Summary of leakage parameters determined for a circumferential crack with crack length and width of 100mm and 1m respectively.

Pipe Sample	C_d	C	N1	m (m)	A_0 (m^2)
uPVC	0.5019	3.866 x 10^{-04}	0.3274	-2.276 x 10^{-07}	1.000 x 10^{-04}

Table 4.15 compares the experimental data to the FAVAD and N1 equations of the uPVC sample. Both the R^2 values are high with an average of 97%, showing a good fit. The SSE values are also low, showing a small random error component.

Table 4.15: Statistical comparison of the N1 and FAVAD equations with the experimental data for a circumferential crack of length 100mm and width 1mm.

Pipe Sample	R^2		SSE	
	N1	FAVAD	N1	FAVAD
uPVC	0.96681	0.96691	1.454 x 10^{-04}	1.418 x 10^{-04}
Average	**0.96681**	**0.96691**	**1.454 x 10^{-04}**	**1.418 x 10^{-04}**

4.3.4 Discussion

The results clearly show that circumferential cracks decrease in area with an increase in the pressure head. This is due to the circumferential stresses being greater than the longitudinal stresses in a pipe. It is also evident that the larger the crack length, the larger the contraction of the leak area.

The negative exponent of -0.26 for the HDPE 75mm sample is a rare finding. Negative exponents only occur when the flows gradually decrease with an increase in pressure. The low exponent of 0.19 for the HDPE 50mm also has significance as exponents this low are also rare in the literature.

Table 4.16 shows the comparison between the experimental data with the N1 and FAVAD equations for circumferential cracks. The N1 and FAVAD equations had the closest correlation for the uPVC 100mm sample. However, the HDPE 50mm sample had a low R^2 value and the HDPE 75mm sample had an even lower R^2 value. This shows that the material properties influence the variation in the data that the N1 and FAVAD equations cannot explain.

Table 4.16: Statistical comparison of the N1 and FAVAD equations with the experimental data for circumferential cracks.

Crack length	R^2		SSE	
	N1	**FAVAD**	**N1**	**FAVAD**
50mm	0.85739	0.86325	6.534×10^{-05}	6.542×10^{-05}
75mm	0.25106	0.27516	2.900×10^{-05}	3.271×10^{-05}
100mm	0.96681	0.96691	1.454×10^{-04}	1.418×10^{-04}
Average	**0.69175**	**0.70177**	$\mathbf{7.991 \times 10^{-05}}$	$\mathbf{7.998 \times 10^{-05}}$

In general, the N1 and FAVAD equations had a reasonable fit with the experimental data at an average of 70%. However, the random error components for both the N1 and the FAVAD equations are very small.

4.4 Spiral Cracks

4.4.1 50mm

Four experiments (04, 10, 16, 23) were carried out on spiral cracks with an approximate length of 50mm and a width of 1mm. The four pipe materials were mPVC, HDPE, steel and uPVC.

Figure 4.19 shows the experimental data for all four materials. The mPVC sample has the highest flows. uPVC is next, closely followed by the HDPE. The steel sample has the lowest flows once again.

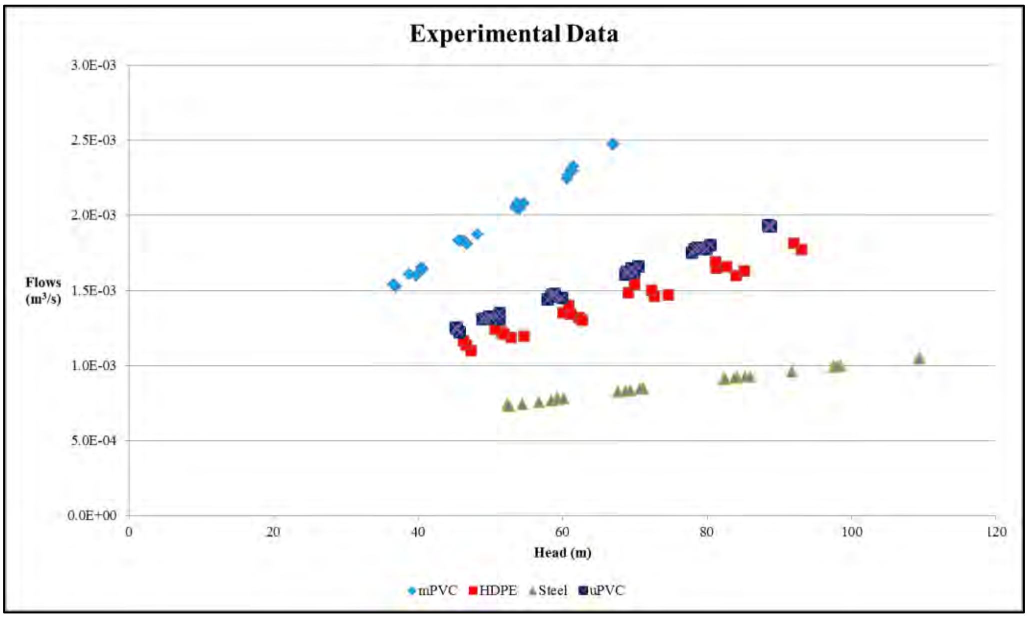

Figure 4.19: Experimental data for each pipe sample with a spiral crack of length 50mm and width 1mm.

Figure 4.20 shows the N1 and FAVAD equations for all the pipe materials. The equations follow a similar pattern to the experimental data. Steel has the lowest flows, and both the equations are very similar as they line up consistently. The HDPE and uPVC N1 and FAVAD equations are also very similar with a slight variation in flows around the 40 m of head mark after which the equations meet. The HDPE FAVAD equation then starts to increase above the N1 equation above 80 of head. The uPVC FAVAD equation dips below the N1 equation at about 50 m of head and then re-joins the N1 equation as they approach 100 m of pressure head. The HDPE equations had the highest flows and largest variation between them; the FAVAD equation is always above the N1 equation but the distance above the N1 equation varies with increasing pressure.

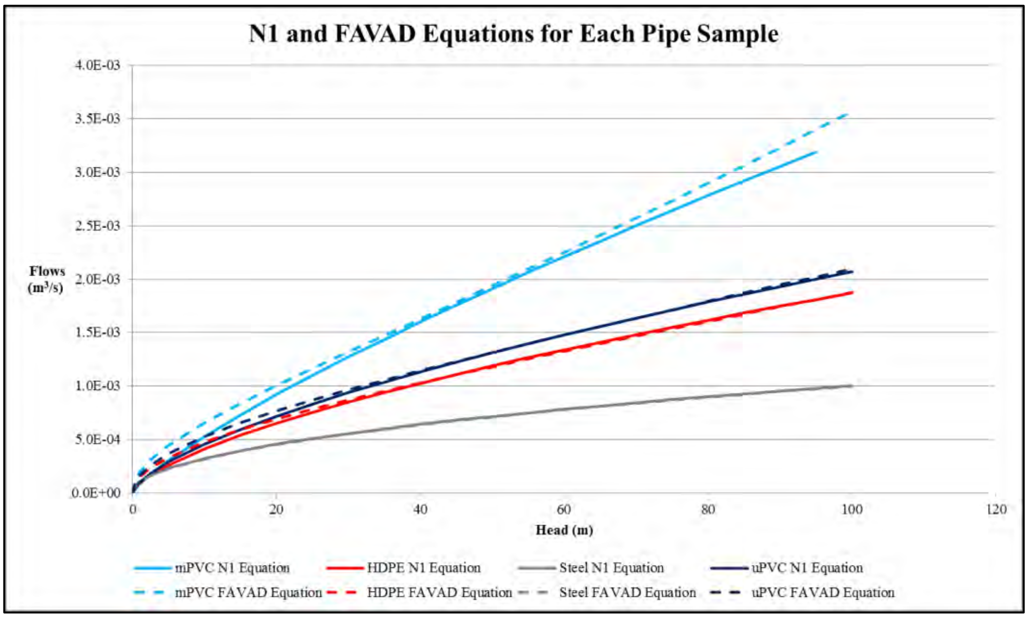

Figure 4.20: N1 and FAVAD equations for spiral cracks with length 50mm and width 1mm.

Figure 4.21 shows how the area varies with the pressure head for each of the samples. Here three pipe samples expand with increasing pressure and one contracts. mPVC had the largest expansion followed by HDPE and then uPVC. The steel sample contracted but only by a small amount which can be seen by the very gentle negative slope m.

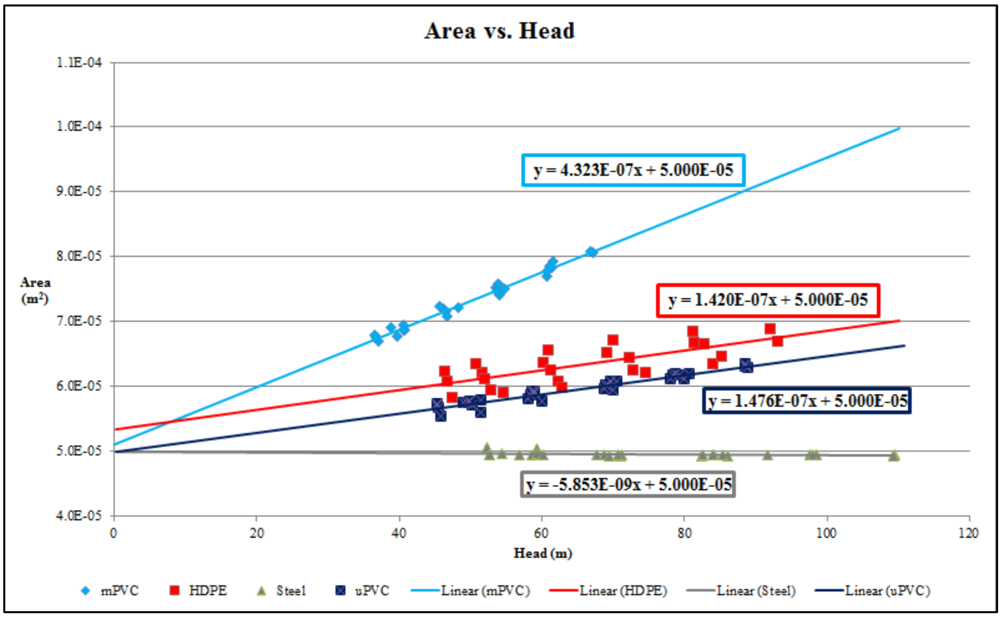

Figure 4.21: Leak area against head for spiral cracks of length 50mm and width 1mm.

Table 4.17 summarises the leakage parameters for spiral cracks with a length of 75mm. All the parameters vary for different pipe materials. Steel has the lowest C_d value at 0.4569 and mPVC has the highest with 0.8646. Steel also has the highest C value at 1.04 x 10^{-04} whereas mPVC has the lowest C value at 9.04 x 10^{-05}. mPVC, HDPE and uPVC all have a N1 value of greater than 0.50 indicting expansion of the leak area. Steel was the only sample to have a N1 value less than 0.50 and hence a negative slope m.

Table 4.17: Summary of leakage parameters determined for spiral cracks with crack length and width of 50mm and 1m respectively.

Pipe Sample	C_d	C	N1	m (m)	A_0 (m^2)
mPVC	0.8646	9.045 x 10^{-05}	0.7983	4.323 x 10^{-07}	5.000 x 10^{-05}
HDPE	0.6602	9.115 x 10^{-05}	0.6563	1.420 x 10^{-07}	5.000 x 10^{-05}
Steel	0.4569	1.045 x 10^{-04}	0.4905	-5.853 x 10^{-09}	5.000 x 10^{-05}
uPVC	0.7318	1.004 x 10^{-04}	0.6574	1.476 x 10^{-07}	5.000 x 10^{-05}

Table 4.18 compares the experimental data to the N1 and FAVAD equations. The R^2 values for both the N1 and FAVAD equations show a good fit with an average of 99%. HDPE was the lowest contributor with 96%. The SSE values are also quite low, with steel having the lowest random error component.

Table 4.18: Statistical comparison of the N1 and FAVAD equations with the experimental data for a circumferential crack of length 50mm and width 1mm.

Pipe Sample	R^2		SSE	
	N1	FAVAD	N1	FAVAD
mPVC	0.99670	0.99729	1.901 x 10^{-04}	1.937 x 10^{-04}
HDPE	0.95647	0.95727	1.033 x 10^{-04}	1.025 x 10^{-04}
Steel	0.99853	0.99848	4.834 x 10^{-05}	4.805 x 10^{-05}
uPVC	0.99589	0.99637	1.504 x 10^{-04}	1.507 x 10^{-04}
Average	**0.98690**	**0.98735**	**1.230 x 10^{-04}**	**1.237 x 10^{-04}**

4.4.2 75mm

Only one experiment (11) was carried out on spiral cracks with a length of a 75mm and a width of 1mm. The pipe material tested was HDPE.

Figure 4.22 shows the experimental data alongside the N1 and FAVAD equations for the HDPE sample. The N1 equation has lower flows than the FAVAD with slight variations as pressure increases. The FAVAD equation has a better fit with the experimental data.

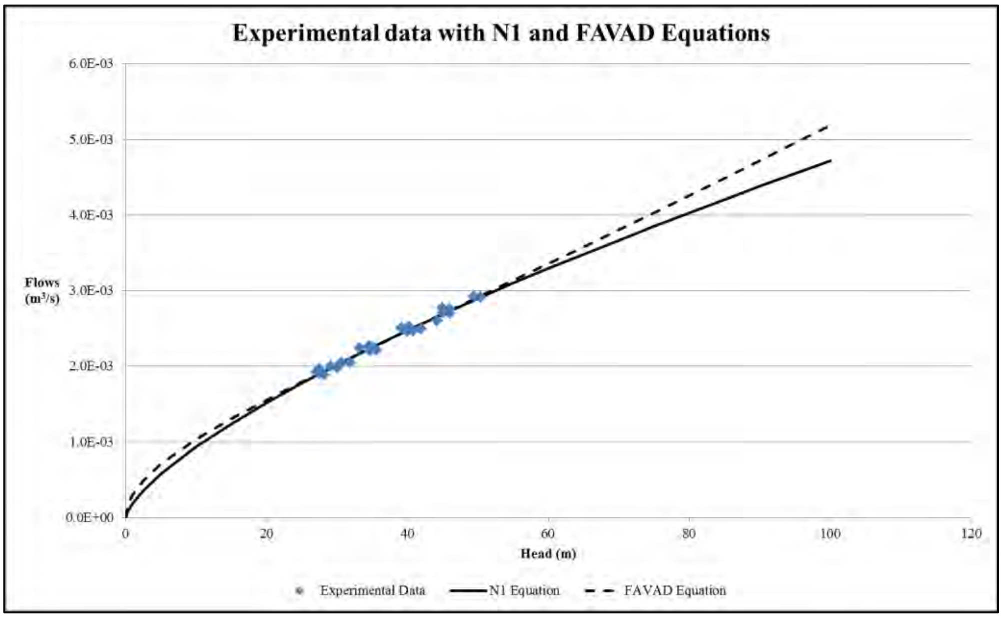

Figure 4.22: Experimental data with the N1 and FAVAD equations for HDPE with a spiral crack of length 75mm and width 1mm.

Figure 4.23 shows the change in area with head or the HDPE sample. The area expands with an increasing head.

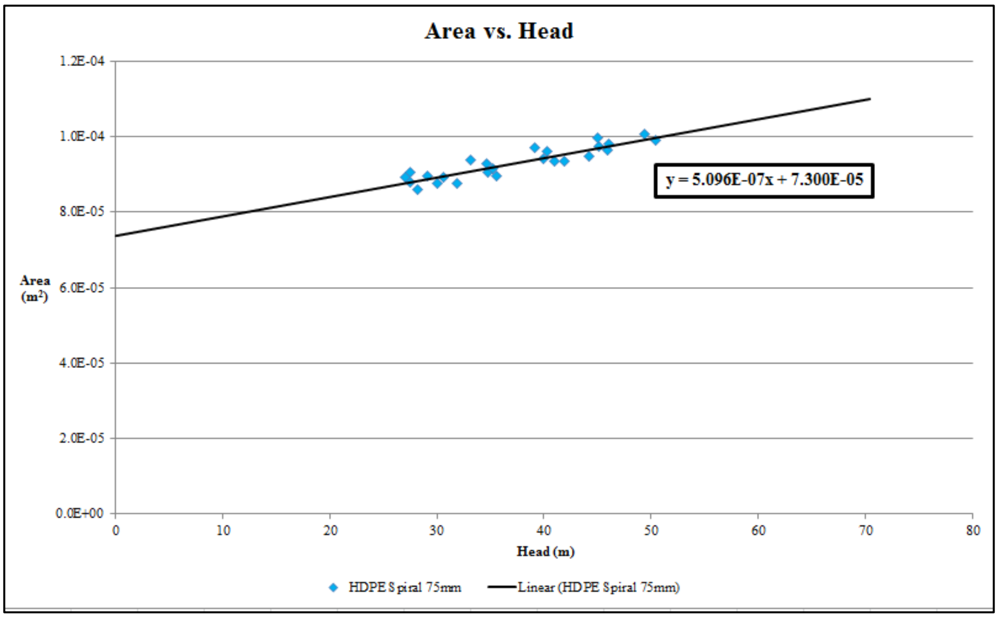

Figure 4.23: Area against head for HDPE with a spiral crack of length 75mm and width 1mm.

Table 4.19 summarises the leakage parameters for the HDPE sample. The C_d value is 0.9449. The C value is 1.86 x 10^{-04}. The leakage exponent is 0.70. The m value shows a steep positive slope.

Table 4.19: Summary of leakage parameters determined for a spiral crack with crack length and width of 75mm and 1m respectively.

Pipe Sample	C_d	C	N1	m (m)	A_0 (m^2)
HDPE	0.9449	1.855×10^{-04}	0.7026	5.096×10^{-07}	7.300×10^{-04}

Table 4.20 compares the experimental data to the N1 and FAVAD equations of the HDPE sample. The N1 and FAVAD equations show a good fit with an R^2 average of 98%. The low SSE values also show a small random error component.

Table 4.20: Statistical comparison of the N1 and FAVAD equations with the experimental data for a longitudinal crack of length 75mm and width 1mm.

Pipe Sample	R^2		SSE	
	N1	FAVAD	N1	FAVAD
HDPE	0.98129	0.98215	2.738×10^{-04}	2.816×10^{-04}
Average	**0.98129**	**0.98215**	$\mathbf{2.738 \times 10^{-04}}$	$\mathbf{2.816 \times 10^{-04}}$

4.4.3 100mm

Two experiments (17, 24) were carried out on spiral cracks with an approximate length of 100mm and a width of 1mm. The pipe materials used were; steel and uPVC.

Figure 4.24 shows the experimental data for both materials. The uPVC sample has a much higher flow range than the steel sample. Similarly, the steel undergoes much higher pressures than the uPVC.

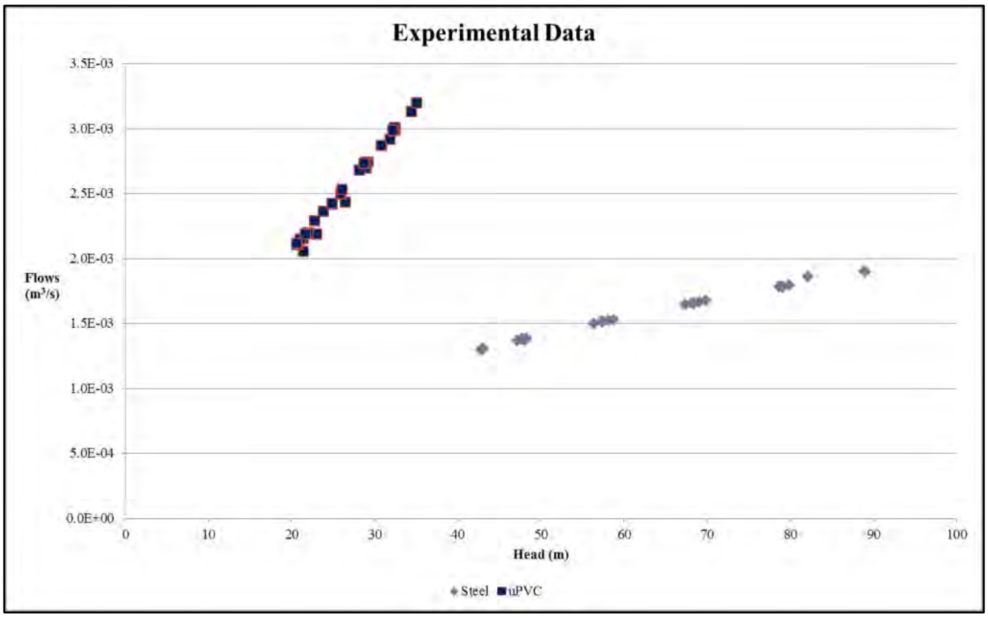

Figure 4.24: Experimental data for each pipe sample with a spiral crack of length 100mm and width 1mm.

Figure 4.25 shows the N1 and FAVAD equations for both pipe materials. The steel N1 and FAVAD equations are almost identical with any differences visually unnoticeable from the graph. The uPVC FAVAD equation starts off above the N1 equation and re-joins the N1 equation between 20 to 35 m of head. Thereafter the flows of the FAVAD equation increase rapidly above the N1 equation.

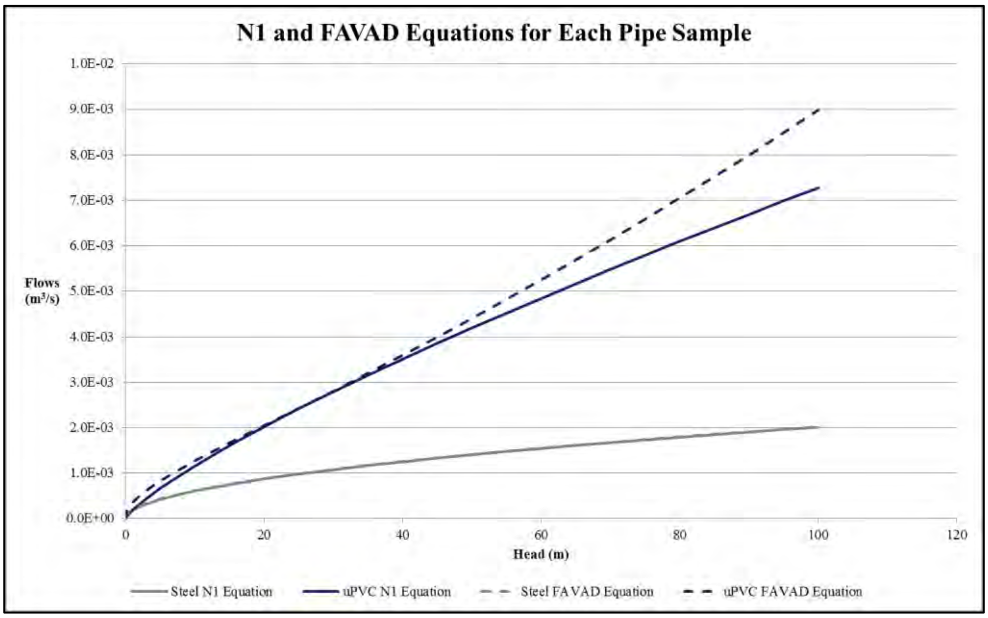

Figure 4.25: N1 and FAVAD equations for spiral cracks with length 100mm and width 1mm.

Figure 4.26 shows how the area varies with the pressure head for each of the samples. The uPVC sample has a clear increase in area with a steep slope m. The steel sample has a very small positive slope and therefore the area increases, but only slightly.

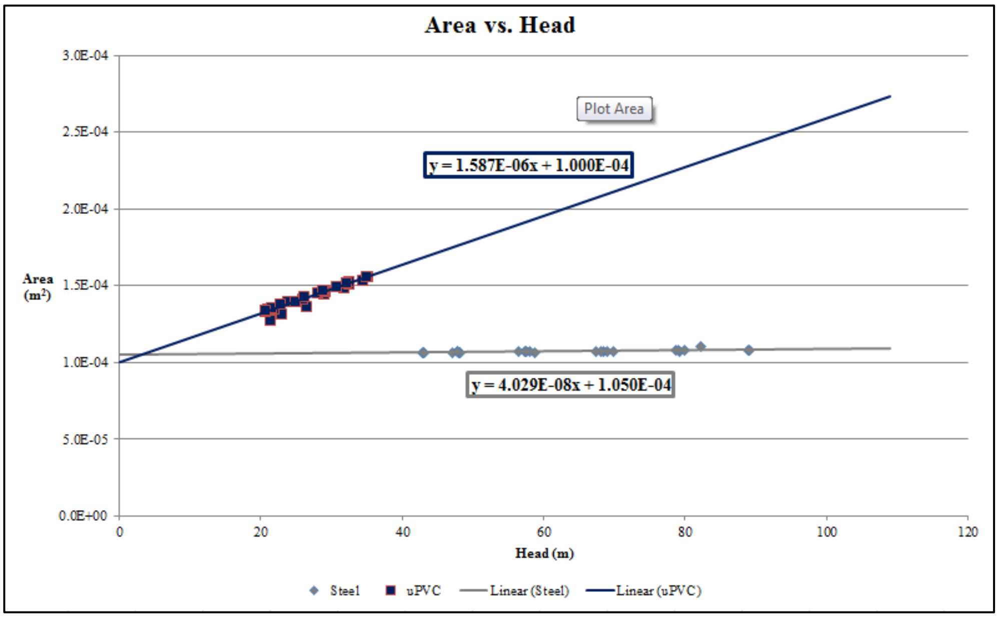

Figure 4.26: Leak area against head for spiral cracks of length 100mm and width 1mm.

Table 4.21 summarises the leakage parameters for spiral cracks with a length of 100mm. Steel has the lower C_d value with 0.4217 compared to the 0.7836 for the uPVC sample. uPVC has a slightly higher C value but they are both consistent to approximately 1.86 x 10^{-04}. The N1 value of 0.52 and m value of 3.20 x 10^{-08} m, for the steel, show that there was minimal expansion for the steel. The uPVC clearly had a greater expansion, shown by the N1 of 0.80 and slope m of 1.59 x 10^{-06}.

Table 4.21: Summary of leakage parameters determined for spiral cracks with crack length and width of 100mm and 1m respectively.

Pipe Sample	C_d	C	N1	m (m)	A_0 (m^2)
Steel	0.4217	1.853 x 10^{-04}	0.5184	3.200 x 10^{-08}	1.050 x 10^{-04}
uPVC	0.7836	1.871 x 10^{-04}	0.7967	1.587 x 10^{-06}	1.000 x 10^{-04}

Table 4.22 compares the experimental data to the N1 and FAVAD equations for both samples. The average R^2 value for both equations was high with almost 100%, showing a good fit for both equations. The low SSE values also show small random error components for both equations.

Table 4.22: Statistical comparison of the N1 and FAVAD equations with the experimental data for a spiral crack of length 100mm and width 1mm.

Pipe Sample	R^2		SSE	
	N1	**FAVAD**	**N1**	**FAVAD**
Steel	0.99983	0.99983	1.362×10^{-04}	1.367×10^{-04}
uPVC	0.99041	0.99092	4.161×10^{-04}	4.195×10^{-04}
Average	**0.99512**	**0.99538**	$\mathbf{2.762 \times 10^{-04}}$	$\mathbf{2.781 \times 10^{-04}}$

4.4.4 Discussion

The results show that in general, spiral cracks expand in area with an increase in pressure. This is true for all the pipe samples tested, apart from the steel 50mm. For the steel 50mm sample, the steel pipe seems to provide resistance in the longitudinal direction, allowing the circumferential stresses to close the leak opening.

Table 4.23 shows a comparison between the experimental data and the N1 and FAVAD equations for spiral cracks. The N1 and FAVAD equations are successful in predicting the behaviour of spiral leaks which is shown by the high R^2 and low SSE values.

Table 4.23: Statistical comparison of the N1 and FAVAD equations with the experimental data for spiral cracks.

Crack length	R^2		SSE	
	N1	**FAVAD**	**N1**	**FAVAD**
50mm	0.98690	0.98735	1.230×10^{-04}	1.237×10^{-04}
75mm	0.98129	0.98215	2.738×10^{-04}	2.816×10^{-04}
100mm	0.99512	0.99538	2.762×10^{-04}	2.781×10^{-04}
Average	**0.98777**	**0.98829**	$\mathbf{2.243 \times 10^{-04}}$	$\mathbf{2.278 \times 10^{-04}}$

4.5 Overall Discussion

A circular leak area is the most stable shape as it consistently undergoes the least amount of deformation among all the materials. This is evident from the consistency of the leakage parameters between all the materials used. For this reason, when validating the competence of an experimental setup such as the one used in this project, using a sample with a round hole is best as here the leakage parameters can easily be estimated.

The material still has a big influence on the deformation of a circular leak area. The stiffer and less elastic materials (in this case steel and uPVC) show more resistance to deformation; however, the circumferential stresses are still large enough to cause the area to stretch in the circumferential direction, in turn causing the leak area to contract slightly. In the more elastic materials (in this case HDPE and mPVC) there is less resistance to deformation, allowing both the longitudinal and circumferential stresses to have an effect on the leak area, hence resulting in an expansion. Note that the wall thickness also affects how the material deforms.

The longitudinal cracks expanded for all pipe materials and crack lengths tested. Since the circumferential stresses are double the longitudinal stresses as shown by Cassa et al. (2010), the circumferential stresses have a larger effect on the behaviour of a longitudinal crack, whereas, due the orientation of the crack, the longitudinal stresses have less of an effect. Therefore expansion took place for all the longitudinal crack types. HDPE was the most elastic material and showed the greatest expansion, followed by mPVC, uPVC and then steel. The robustness of the steel sample is evident as it showed the smallest expansion compared to the other samples. The crack length definitely plays a large role in leakage behaviour: the longer the crack length, the higher the leakage exponent and the greater the leakage flow.

Circumferential cracks in all pipe materials and for all crack lengths showed a contraction of the leak area. Once again the circumferential stresses have a large effect on the leak area, causing the leak to stretch in the circumferential direction, which reduces the leak width and hence the area. The crack length and material elasticity play a large role in the contraction of circumferential cracks. A longer crack length results in is a larger contraction of the leak area. Similarly, a higher material elasticity will result in greater contraction.

The HDPE samples had displayed unexpected behaviour during testing of the circumferential cracks. A rare negative N1 value of -0.26 was observed for the circumferential 75mm sample. This shows that the leak was unable to stabilise during testing and the flows continued to decrease over the course of the experiment. Another rare exponent was the low N1 of 0.19 from the circumferential 50mm sample. The material had a very steep negative slope and there was a large amount contraction of the leak area. This shows how much effect the material properties can have on the leakage. The N1 and FAVAD R^2 values were also less consistent for the HDPE circumferential cracks. This shows that the N1 and FAVAD equations do not explain much of the variation in the experimental data for HDPE circumferential cracks as compared to the other materials.

In terms of deformation, the behaviour spiral cracks are located in between that of longitudinal and circumferential cracks. For small crack lengths in stiff and dense materials like steel, the circumferential stresses have a larger effect than the longitudinal stresses, causing the leak area to decrease, as seen in the steel 50mm sample. Once the crack length is increased, the longitudinal stresses have a larger effect on the leak area and the leak expands, as seen in the steel 100mm sample. All the plastic materials showed expansions of the leak area. However, the expansions of the spiral cracks were not as large as those of the longitudinal cracks. The crack length and elasticity of the material once again play a large role in the deformation of the leak area. Similarly to the longitudinal cracks, a longer spiral crack length results in a larger expansion. The same is true for a material with higher elasticity.

The effective area (equation 21) is an important factor as it is required when determining the Coefficient of Discharge (C_d) and Head-area slope (m) of a pipe with an individual leak.

When the orifice equation is generalised to form the N1 equation, C is equivalent to the effective area, and therefore a comparisons of C values was used to observe the behaviour of the effective area. Table 4.24 shows the C values for all the tested samples. It should be noted that the boxes of dark blue were unavailable samples.

Table 4.24: Leakage coefficients for all tested pipe samples.

Leak Type	Leakage Coefficient (C)			
	mPVC	**HDPE**	**Steel**	**uPVC**
Round Hole 12mm	3.02×10^{-04}	3.10×10^{-04}	3.02×10^{-04}	3.03×10^{-04}
Longitudinal 50mm	5.24×10^{-05}	2.45×10^{-04}	9.74×10^{-05}	4.42×10^{-05}
Longitudinal 75mm		1.30×10^{-04}		
Longitudinal 100mm			1.81×10^{-04}	8.58×10^{-05}
Circumferential 50mm	2.05×10^{-05}	2.72×10^{-04}	1.01×10^{-04}	1.76×10^{-04}
Circumferential 75mm		2.47×10^{-03}		
Circumferential 100mm				3.87×10^{-04}
Spiral 50mm	8.75×10^{-05}	9.05×10^{-05}	1.05×10^{-04}	
Spiral 75mm		1.86×10^{-04}		1.00×10^{-04}
Spiral 100mm			1.85×10^{-04}	1.87×10^{-04}

Table 4.24 shows that the C values have a large variation between different materials and leak types, apart from the round hole. The steel samples have consistent C values, with minimal variation across the different crack types. The plastic pipe samples have more variation in their C values across the different leak types. No pattern can be seen between crack length and the C value, and hence between the crack length and the effective area.

In general, longitudinal cracks showed the largest amount of expansion followed by spiral cracks. Round holes showed the least amount of deformation, whereas circumferential cracks showed a contraction in the leak area for all test samples. The leakage exponents ranged from -0.26 to 1.05 for all pipe material and leak types.

Table 4.25 shows the comparison between the experimental data and N1 and FAVAD equations for all leak types. The average R^2 values of 91% show that the N1 and FAVAD equations explain the variation of the experimental data very well. The circumferential cracks showed the lower correlation but that could have to do with the HDPE pipe material which was used for two of the circumferential cracks, since the material properties clearly displayed a unique behaviour. The average SSE values are also low, which shows that the N1 and

FAVAD equations have very small random error components when predicting the behaviour of individual leaks. However, the average of the R^2 and SSE values also show that the FAVAD equation had a slightly better correlation to the experimental data than the N1 equation, whereas the N1 equation has a slightly smaller random error component than the FAVAD equation.

Table 4.25: Statistical comparison of the N1 and FAVAD equations with the experimental data for all leak types.

Leak Type	**R^2**		**SSE**	
	N1	**FAVAD**	**N1**	**FAVAD**
Round Holes	0.99988	0.99988	2.663×10^{-04}	2.664×10^{-04}
Longitudinal	0.96910	0.96992	2.436×10^{-04}	2.535×10^{-04}
Circumferential	0.69175	0.70177	7.991×10^{-05}	7.998×10^{-05}
Spiral	0.98777	0.98829	2.243×10^{-04}	2.278×10^{-04}
Average	**0.91212**	**0.91497**	**2.035×10^{-04}**	**2.069×10^{-04}**

5 Conclusion

This chapter summarises the main finding of the investigation and discusses recommendations for further work.

5.1 Summary of the Study

This investigation had two aims. The first aim was to develop a standard experimental procedure to determine the leakage parameters of a pipe with an individual leak. The second aim was to test a series of pipes using the developed standard procedure and determine their leakage parameters. Drawing on a literature review, an experimental procedure was developed which enables a pipe with an individual leak to be examined under a range of pressures.

An experimental setup was designed to contain a pipe under high internal pressure as well as be efficient at replacing pipe samples. A data analysis process was developed and improved for efficiency.

A verification process was used to ensure the efficiency and competence of the experimental procedure. This was done by means of a repeatability analysis, pilot experiments and a sensitivity analysis. The results showed that the experimental procedure was competent, but some minor adjustments were made to improve the efficiency of the experimental setup and accuracy of the results.

Using the improved experimental procedure, four pipe materials (mPVC, HDPE, steel and uPVC) and four leak types (round hole, circumferential, longitudinal and spiral cracks) were tested and their leakage parameters determined.

The leakage parameters determined for each pipe sample were: the leakage coefficient (C), the Coefficient of Discharge (C_d), the leakage exponent (N1), the initial leak area (A_0) and the head-area slope (m). These leakage parameters helped to understand the behaviour of the material and its respective leak type.

The leakage parameters were also substituted into the N1 and FAVAD equations. This enabled the development of a set of data points which were used to compare the N1 and FAVAD equations to the experimental data. This comparison was made using two simple statistical tools, the Coefficient of Correlation (R^2) and the Sum of Squared Errors (SSE).

5.2 Main Conclusions

Round holes were found to be the most stable leak shapes with the least amount of deformation. All the pipe samples with round hole leaks had an exponent of 0.50 to two decimal places. The m values showed very gentle slopes for all samples.

Longitudinal cracks experienced a large amount of deformation in terms of expansion. The N1 values ranged from 0.50 to 1.05, with steel samples showing the lowest expansion and the plastics showing varied expansions.

Circumferential cracks also experience large amounts of deformation but in terms of contraction. N1 values ranged from 0.33 to 0.49 with the exception of two rare findings, namely a very low N1 value of 0.19 for the HDPE 50mm sample as well as a negative exponent of -0.26 for the HDPE 75mm sample. These two findings are directly related to the material's elastic properties and are a result of the leak not being able to stabilise during the course of the experiment.

Spiral cracks also experienced deformations in form of expansions apart from the steel 50mm sample which contracted in area. The spiral cracks had a range of 0.49 to 0.80. The slope m for the plastic materials were high in all instances.

The N1and FAVAD R^2 average for all leak types and pipe materials is 0.91. This shows that both the N1 and FAVAD equations had a good fit with the experimental data. The N1 and FAVAD SSE values were also low with an average of 2.05 x 10^{-04}. This shows that both the equations have small random error components when predicting the behaviour of the leaks used in this investigation. The only significant difference between the two equations is that the FAVAD equation had a slightly higher R^2 value and the N1 equation had a slightly lower SSE value.

Overall, the standard experimental procedure developed was effective in determining accurate leakage parameters for the various pipe samples. The leakage parameters determined were successful in evaluating the N1 and FAVAD equations. Both the equations succeeded in predicting the behaviour of the various leak types.

5.3 Recommendations for Further Work

The main recommendations to be made are within the experimental procedure. The process of setting up the pipe sample is labour intensive and time consuming. If this process could be automated with the use of hydraulic machinery, it would improve the efficiency of the experimental setup and more pipe samples could be tested. To avoid settling-in points, the pressure head should be gradually increased and maintained at high pressure for approximately 30 seconds, followed by a gradual decrease in the pressure head. This should allow sufficient exposure of the leak to the change in pressure and stabilise the leak.

The FAVAD equation had a higher R^2 value and the N1 equation had a lower SSE value. The reason for this is still unknown, therefore a more detailed statistical analysis is required to further understand the behaviour of the leak outflow and the N1 and FAVAD equations.

Further investigation is also required on the effect of pressure on highly elastic materials as well as the visco-elastic behaviour of plastics to better understand the relationship between pressure and leakage.

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APPENDICES

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Experiment 11: HDPE Spiral 75mm

Experiment 11 (omitted): HDPE Spiral 75mm

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Experiment 14: Steel Longitudinal 100mm

Experiment 14 (omitted): Steel Long 100mm

Experiment 15: Steel Round Hole 12mm

Experiment 15 (omitted): Steel Round Hole 12mm

Experiment 16: Steel Spiral 50mm

Experiment 17: Steel Spiral 100mm

Experiment 17 (omitted): Steel Spiral 100mm

Experiment 18: uPVC Circumferential 50mm

Experiment 19: uPVC Circumferential 100mm

Experiment 20: uPVC Longitudinal 50mm

Experiment 20 (omitted): uPVC Longitudinal 50mm

Experiment 21: uPVC Longitudinal 100mm

Experiment 22: uPVC Round Hole 12mm

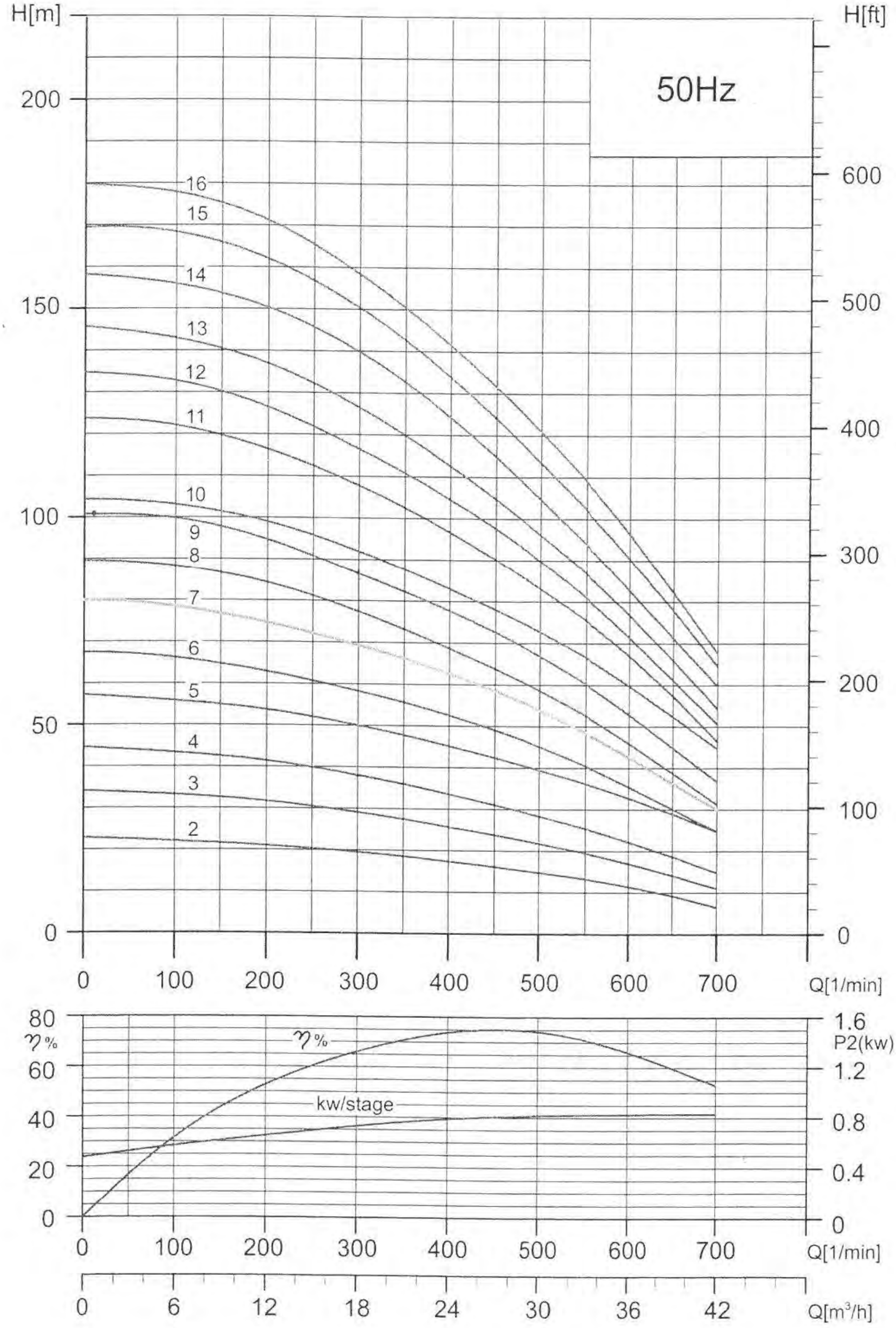
Experiment 23: uPVC Spiral 50mm

Experiment 24: uPVC Spiral 100mm

APPENDIX A:

Electro-magnetic Flow Meter, Calibration Certificate and Submersible Pump Curve

Aquanox | Performance Curves | QFN50



Salmson FTT
A WILO BRAND

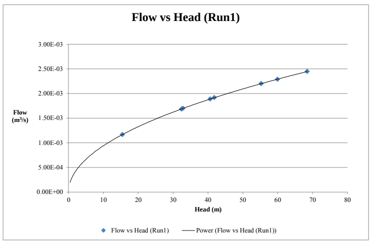
APPENDIX B:
Verification Experiments

Repeatability Analysis: Steel Round Hole 12mm

1 Bar =	**10.1940**	**m**
1 l/s =	**0.0010**	**m^3/s**
A_0 =	**1.131E-04**	**m^2**

Sample	**Flow (l/s)**	**Pressure (bar)**	**Final Flow Readings (m^3/s)**	**Head (m)**	**C_dA**	**A**		
1.1	1.1664	1.5121	1.166E-03	15.4148	6.707E-05	1.130E-04	C_dA_0 =	6.710E-05
1.2	1.6857	3.1786	1.686E-03	32.4028	6.685E-05	1.127E-04	C_d =	5.933E-01
1.3	1.8893	3.9862	1.889E-03	40.6353	6.691E-05	1.128E-04	m =	-7.937E-09
1.4	2.2019	5.4193	2.202E-03	55.2441	6.688E-05	1.127E-04		
1.5	2.4479	6.7150	2.448E-03	68.4526	6.680E-05	1.126E-04		
1.6	2.2901	5.8800	2.290E-03	59.9406	6.678E-05	1.126E-04		
1.7	1.9170	4.1014	1.917E-03	41.8099	6.693E-05	1.128E-04		
1.8	1.6989	3.2186	1.699E-03	32.8101	6.696E-05	1.129E-04		
2.1	1.2113	1.6173	1.211E-03	16.4871	6.735E-05	1.131E-04	C_dA_0 =	6.734E-05
2.2	1.6910	3.1880	1.691E-03	32.4984	6.697E-05	1.125E-04	C_d =	5.954E-01
2.3	1.8767	3.9373	1.877E-03	40.1371	6.688E-05	1.123E-04	m =	-1.592E-08
2.4	2.1888	5.3680	2.189E-03	54.7213	6.680E-05	1.122E-04		
2.5	2.4507	6.7276	2.451E-03	68.5809	6.681E-05	1.122E-04		
2.6	2.1843	5.3400	2.184E-03	54.4359	6.684E-05	1.123E-04		
2.7	1.8576	3.8566	1.858E-03	39.3136	6.688E-05	1.123E-04		
2.8	1.6987	3.2207	1.699E-03	32.8319	6.693E-05	1.124E-04		
2.9	1.0925	1.3200	1.093E-03	13.4561	6.724E-05	1.129E-04		
3.1	1.1476	1.4607	1.148E-03	14.8902	6.714E-05	1.129E-04	C_dA_0 =	6.725E-05
3.2	1.6919	3.1960	1.692E-03	32.5800	6.692E-05	1.125E-04	C_d =	5.947E-01
3.3	1.8948	4.0027	1.895E-03	40.8031	6.697E-05	1.126E-04	m =	-1.428E-08
3.4	2.2249	5.5441	2.225E-03	56.5169	6.681E-05	1.124E-04		
3.5	2.4474	6.7353	2.447E-03	68.6599	6.668E-05	1.121E-04		
3.6	2.2339	5.6060	2.234E-03	57.1475	6.672E-05	1.122E-04		
3.7	1.9117	4.0807	1.912E-03	41.5983	6.692E-05	1.125E-04		
3.8	1.6997	3.2253	1.700E-03	32.8790	6.692E-05	1.125E-04		
3.9	1.3495	2.0220	1.350E-03	20.6122	6.711E-05	1.128E-04		
4.1	0.8371	0.7793	8.371E-04	7.9443	6.705E-05	1.131E-04	C_dA_0 =	6.706E-05
4.2	1.6908	3.1972	1.691E-03	32.5926	6.686E-05	1.128E-04	C_d =	5.929E-01
4.3	1.8750	3.9240	1.875E-03	40.0012	6.693E-05	1.129E-04	m =	-7.922E-09
4.4	2.2146	5.5207	2.215E-03	56.2776	6.665E-05	1.124E-04		
4.5	2.4496	6.7300	2.450E-03	68.6055	6.677E-05	1.126E-04		
4.6	2.2238	5.5353	2.224E-03	56.4271	6.683E-05	1.127E-04		
4.7	1.8641	3.8828	1.864E-03	39.5808	6.689E-05	1.128E-04		
4.8	1.7007	3.2240	1.701E-03	32.8654	6.697E-05	1.130E-04		
4.9	1.0276	1.1786	1.028E-03	12.0143	6.693E-05	1.129E-04		
5.1	1.1289	1.4173	1.129E-03	14.4483	6.705E-05	1.130E-04	C_dA_0 =	6.710E-05
5.2	1.6931	3.2007	1.693E-03	32.6280	6.692E-05	1.128E-04	C_d =	5.933E-01
5.3	1.8663	3.8980	1.866E-03	39.7362	6.684E-05	1.127E-04	m =	-8.638E-09
5.4	2.2057	5.4393	2.206E-03	55.4483	6.687E-05	1.127E-04		
5.5	2.4506	6.7393	2.451E-03	68.7007	6.675E-05	1.125E-04		
5.6	2.2514	5.6787	2.251E-03	57.8882	6.680E-05	1.126E-04		
5.7	1.9303	4.1680	1.930E-03	42.4885	6.685E-05	1.127E-04		
5.8	1.7007	3.2320	1.701E-03	32.9470	6.689E-05	1.128E-04		
5.9	1.1428	1.4524	1.143E-03	14.8059	6.705E-05	1.130E-04		

Repeatability Analysis: Steel Round Hole 12mm



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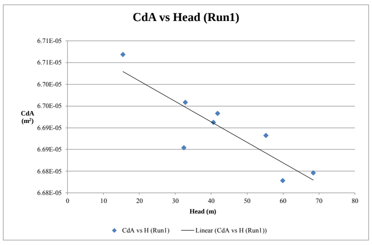

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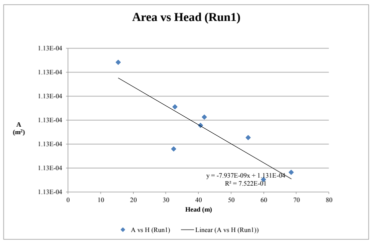

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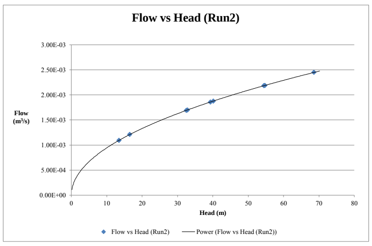

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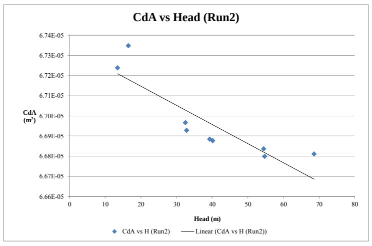

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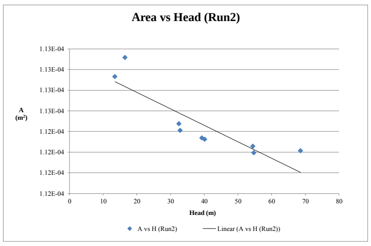

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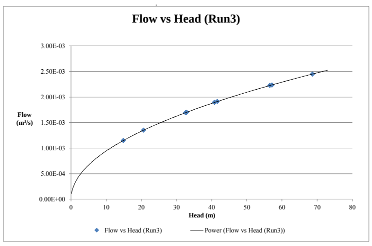

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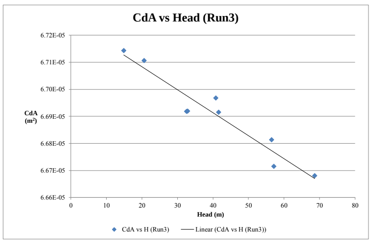

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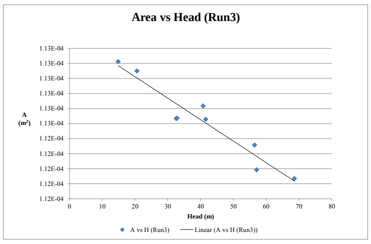

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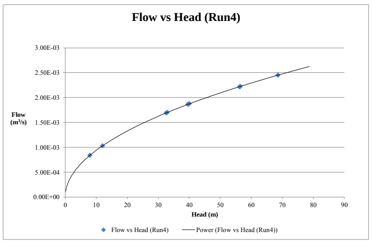

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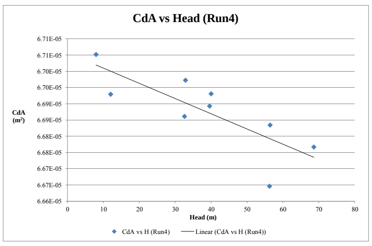

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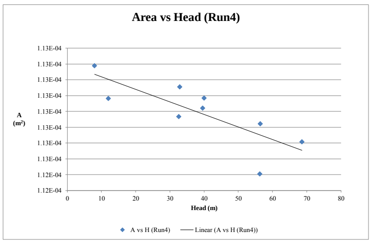

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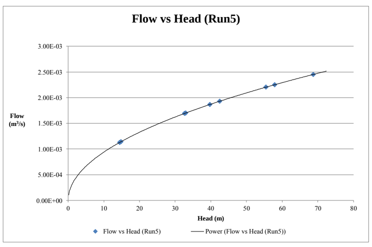

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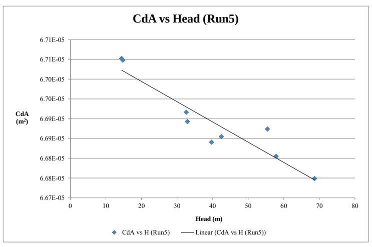
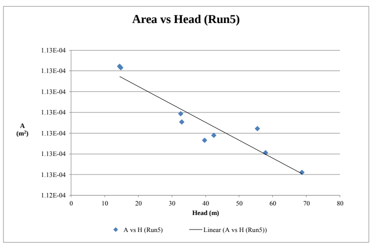


$y = -5.120E-09x + 6.708E-05$
$R^2 = 8.776E-01$



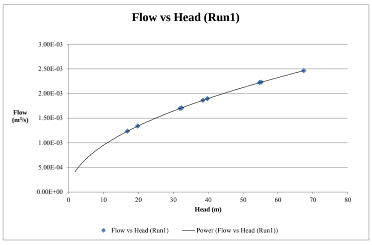
$y = -8.554E-09x + 1.121E-04$
$R^2 = 8.776E-01$

Repeatability Analysis: uPVC Round Hole 12mm

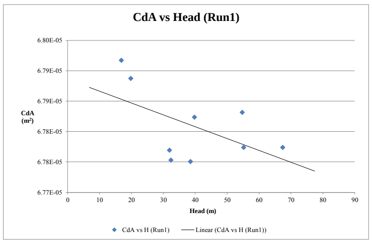
1 Bar =	**10.1940**	**m**
1 l/s =	**0.0010**	**m^3/s**
A_0 =	**1.131E-04**	**m^2**

Sample	Flow (l/s)	Pressure (bar)	Final Flow Readings (m^3/s)	Head (m)	C_dA	A		
1.1	1.2349	1.6529	1.235E-03	16.8492	6.792E-05	1.131E-04	C_dA_0 =	6.789E-05
1.2	1.6966	3.1336	1.697E-03	31.9436	6.777E-05	1.129E-04	C_d =	0.6002
1.3	1.8622	3.7771	1.862E-03	38.5041	6.775E-05	1.129E-04	m =	-3.251E-09
1.4	2.2229	5.3693	2.223E-03	54.7344	6.783E-05	1.130E-04		
1.5	2.4648	6.6129	2.465E-03	67.4114	6.777E-05	1.129E-04		
1.6	2.2304	5.4152	2.230E-03	55.2022	6.777E-05	1.129E-04		
1.7	1.8947	3.9020	1.895E-03	39.7769	6.782E-05	1.130E-04		
1.8	1.7078	3.1767	1.708E-03	32.3829	6.775E-05	1.129E-04		
1.9	1.3382	1.9427	1.338E-03	19.8035	6.789E-05	1.131E-04		
2.1	1.3424	1.9636	1.342E-03	20.0166	6.774E-05	1.127E-04	C_dA_0 =	6.799E-05
2.2	1.7052	3.1510	1.705E-03	32.1216	6.792E-05	1.130E-04	C_d =	0.6011
2.3	1.9379	4.0793	1.938E-03	41.5847	6.785E-05	1.129E-04	m =	-5.337E-09
2.4	2.3040	5.7621	2.304E-03	58.7384	6.787E-05	1.129E-04		
2.5	2.4732	6.6307	2.473E-03	67.5929	6.791E-05	1.130E-04		
2.6	2.2682	5.6138	2.268E-03	57.2269	6.769E-05	1.126E-04		
2.7	1.9066	3.9613	1.907E-03	40.3818	6.773E-05	1.127E-04		
2.8	1.7102	3.1800	1.710E-03	32.4169	6.781E-05	1.128E-04		
2.9	0.9022	0.8752	9.022E-04	8.9215	6.819E-05	1.134E-04		
3.1	1.4508	2.2836	1.451E-03	23.2787	6.788E-05	1.132E-04	C_dA_0 =	6.781E-05
3.2	1.7016	3.1520	1.702E-03	32.1314	6.777E-05	1.130E-04	C_d =	0.5996
3.3	1.8745	3.8187	1.874E-03	38.9274	6.783E-05	1.131E-04	m =	2.067E-09
3.4	2.2589	5.5464	2.259E-03	56.5402	6.782E-05	1.131E-04		
3.5	2.4734	6.6255	2.473E-03	67.5404	6.795E-05	1.133E-04		
3.6	2.2434	5.4545	2.243E-03	55.6029	6.792E-05	1.133E-04		
3.7	1.9072	3.9493	1.907E-03	40.2594	6.786E-05	1.132E-04		
3.8	1.7104	3.1793	1.710E-03	32.4101	6.783E-05	1.131E-04		
3.9	1.3961	2.1138	1.396E-03	21.5480	6.790E-05	1.132E-04		
4.1	1.2450	1.6841	1.245E-03	17.1681	6.784E-05	1.132E-04	C_dA_0 =	6.780E-05
4.2	1.7030	3.1593	1.703E-03	32.2062	6.775E-05	1.130E-04	C_d =	0.5995
4.3	1.8982	3.9267	1.898E-03	40.0284	6.774E-05	1.130E-04	m =	-1.231E-09
4.4	2.2422	5.4848	2.242E-03	55.9123	6.770E-05	1.129E-04		
4.5	2.4721	6.6366	2.472E-03	67.6529	6.785E-05	1.132E-04		
4.6	2.2464	5.5007	2.246E-03	56.0737	6.773E-05	1.130E-04		
4.7	1.8877	3.8767	1.888E-03	39.5187	6.779E-05	1.131E-04		
4.8	1.7086	3.1800	1.709E-03	32.4169	6.775E-05	1.130E-04		
4.9	1.3830	2.0793	1.383E-03	21.1967	6.781E-05	1.131E-04		
5.1	1.2533	1.7120	1.253E-03	17.4521	6.773E-05	1.131E-04	C_dA_0 =	6.771E-05
5.2	1.7028	3.1607	1.703E-03	32.2200	6.773E-05	1.131E-04	C_d =	0.5987
5.3	1.9126	3.9945	1.913E-03	40.7197	6.767E-05	1.130E-04	m =	2.104E-09
5.4	2.2326	5.4257	2.233E-03	55.3097	6.777E-05	1.132E-04		
5.5	2.4719	6.6393	2.472E-03	67.6810	6.783E-05	1.133E-04		
5.6	2.2681	5.5972	2.268E-03	57.0582	6.779E-05	1.132E-04		
5.7	1.9221	4.0234	1.922E-03	41.0150	6.776E-05	1.132E-04		
5.8	1.7113	3.1800	1.711E-03	32.4169	6.786E-05	1.133E-04		
5.9	1.3019	1.8460	1.302E-03	18.8181	6.776E-05	1.132E-04		

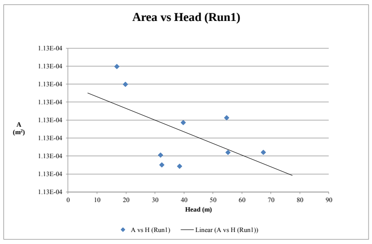
Repeatability Analysis: uPVC Round Hole 12mm



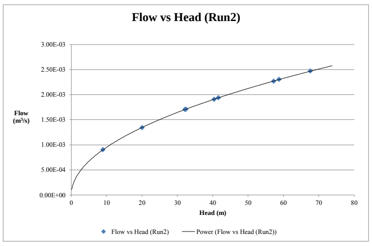
y = $0.0003x^{0.4987}$
R^2 = 1.0000



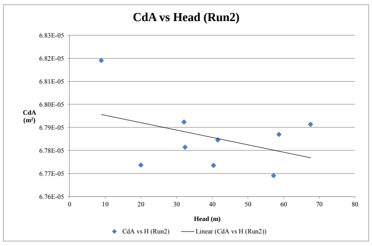
y = -1.951E-09x + 6.789E-05
R^2 = 2.959E-01



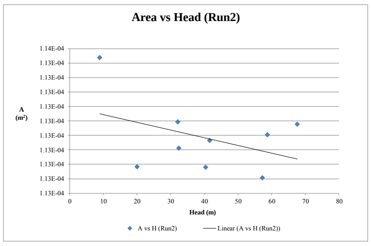
y = -3.251E-09x + 1.131E-04
R^2 = 2.959E-01



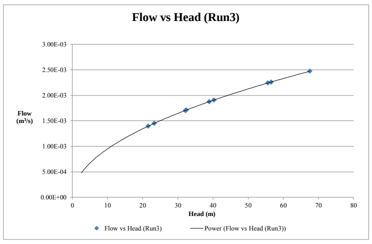
y = $0.0003x^{0.4979}$
R^2 = 1



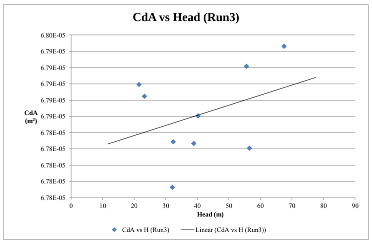
y = -3.208E-09x + 6.799E-05
R^2 = 1.674E-01



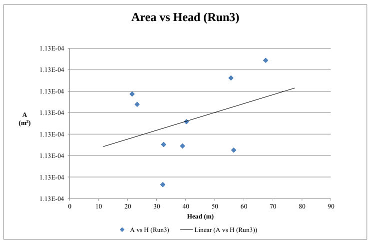
y = -5.337E-09x + 1.131E-04
R^2 = 1.674E-01



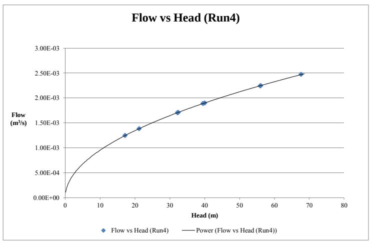
y = $0.0003x^{0.5005}$
R^2 = 1



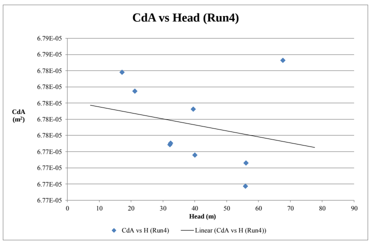
y = 1.239E-09x + 6.781E-05
R^2 = 1.258E-01



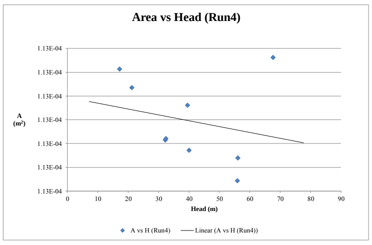
y = 2.067E-09x + 1.131E-04
R^2 = 1.258E-01



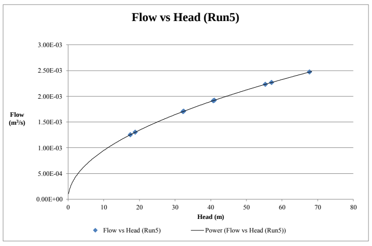
y = $0.0003x^{0.4994}$
R^2 = 1



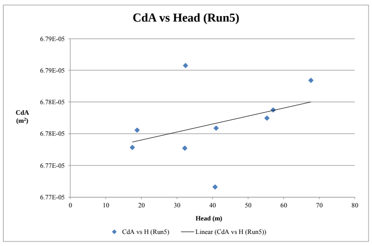
y = -7.378E-10x + 6.780E-05
R^2 = 5.334E-02



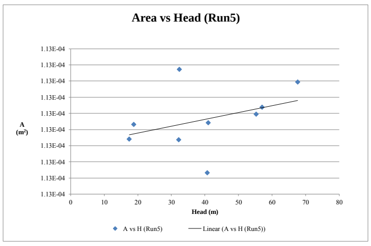
y = -1.231E-09x + 1.131E-04
R^2 = 5.334E-02



y = $0.0003x^{0.5006}$
R^2 = 1



y = 1.260E-09x + 6.771E-05
R^2 = 1.409E-01

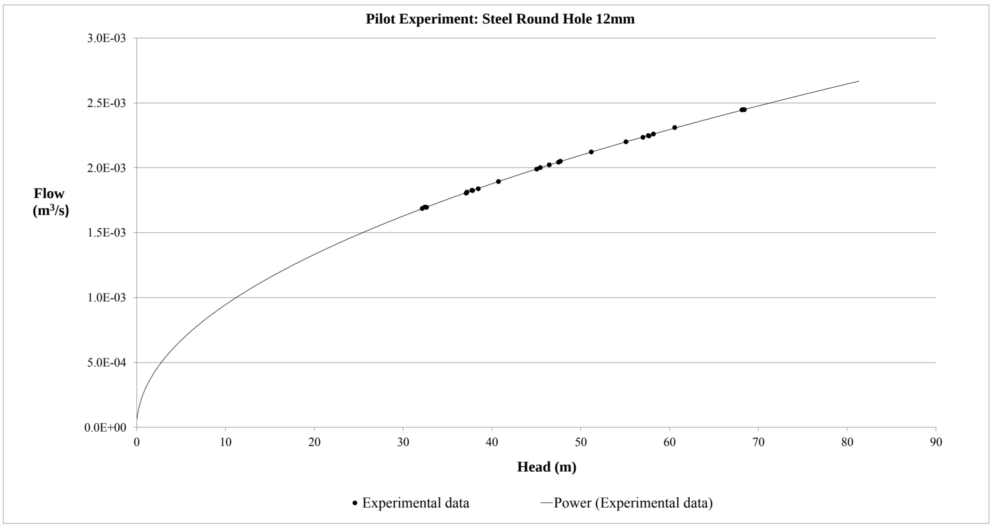


y = 2.104E-09x + 1.131E-04
R^2 = 1.409E-01

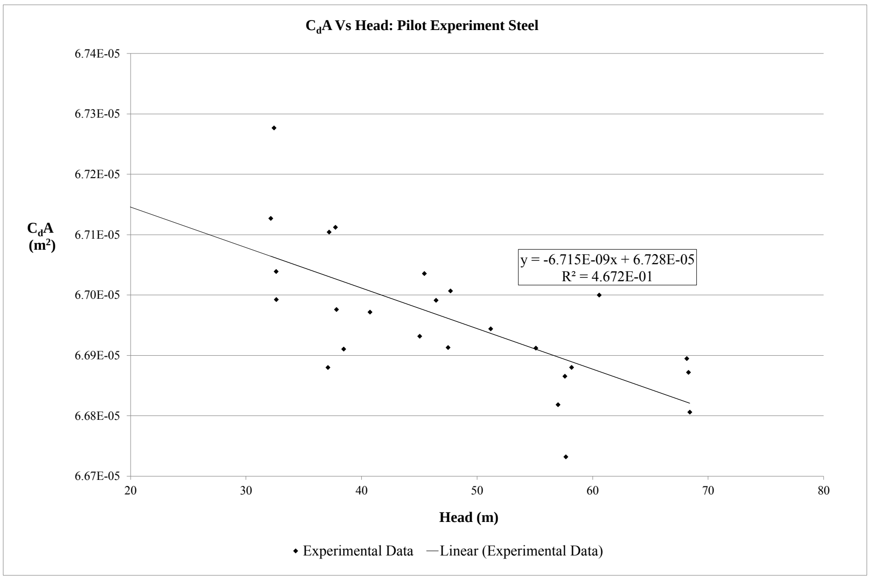
Pilot Experiment: Steel Round 12mm

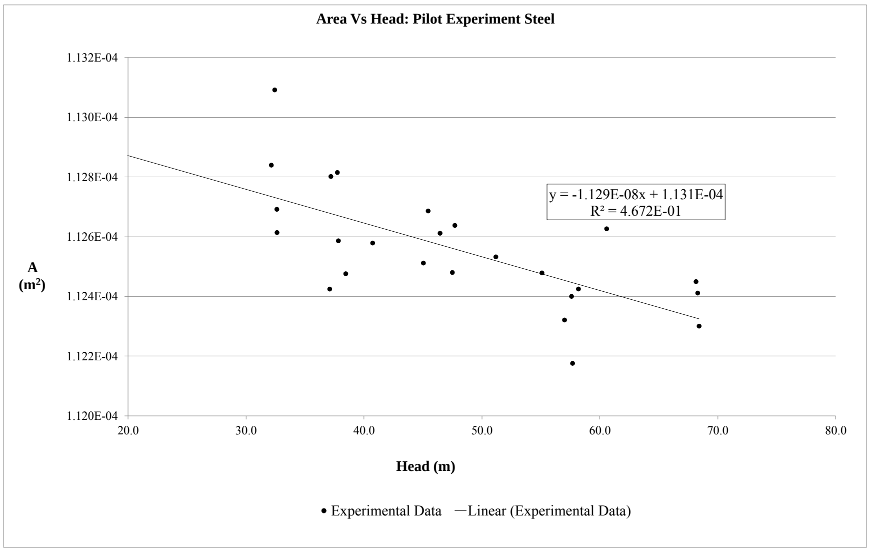
EXPERIMENTAL PARAMETERS		
1 Bar =	10.1937	m
1 l/s =	0.0010	m^3/s
g =	9.81	m/s^2
A_0 =	1.131E-04	m^2
N_1 PARAMETERS		
C =	3.026E-04	
N1 =	0.4948	
FAVAD PARAMETERS		
C_dA_0 =	6.728E-05	m^2
C_d=	0.5949	
m =	-1.129E-08	

Sample	Data Logger Flow (l/s)	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)
1	3.4935	1.6859	3.1538	1.6859E-03	32.1488	6.7127E-05	1.1284E-04
2	3.748	1.8128	3.6489	1.8128E-03	37.1956	6.7104E-05	1.1280E-04
3	4.1029	1.9897	4.4186	1.9897E-03	45.0420	6.6932E-05	1.1251E-04
4	4.5245	2.1999	5.4048	2.1999E-03	55.0951	6.6912E-05	1.1248E-04
5	5.0185	2.4463	6.6864	2.4463E-03	68.1593	6.6895E-05	1.1245E-04
6	4.6445	2.2598	5.7083	2.2598E-03	58.1883	6.6880E-05	1.1242E-04
7	4.1268	2.0016	4.4579	2.0016E-03	45.4427	6.7035E-05	1.1269E-04
8	3.7752	1.8263	3.7028	1.8263E-03	37.7447	6.7112E-05	1.1281E-04
9	3.5159	1.6970	3.1814	1.6970E-03	32.4305	6.7277E-05	1.1309E-04
10	3.7986	1.8380	3.7729	1.8380E-03	38.4593	6.6910E-05	1.1248E-04
11	4.2238	2.0500	4.6800	2.0500E-03	47.7064	6.7007E-05	1.1264E-04
12	4.6150	2.2451	5.6593	2.2451E-03	57.6889	6.6732E-05	1.1218E-04
13	5.0221	2.4480	6.7007	2.4480E-03	68.3045	6.6872E-05	1.1241E-04
14	4.7450	2.3099	5.9430	2.3099E-03	60.5807	6.7000E-05	1.1263E-04
15	4.3671	2.1215	5.0214	2.1215E-03	51.1868	6.6944E-05	1.1253E-04
16	3.9096	1.8934	3.9963	1.8934E-03	40.7370	6.6972E-05	1.1258E-04
17	3.5117	1.6950	3.2007	1.6950E-03	32.6266	6.6992E-05	1.1261E-04
18	3.7311	1.8043	3.6393	1.8043E-03	37.0974	6.6880E-05	1.1242E-04
19	4.2090	2.0426	4.6593	2.0426E-03	47.4958	6.6913E-05	1.1248E-04
20	4.5943	2.2347	5.5929	2.2347E-03	57.0118	6.6818E-05	1.1232E-04
21	5.0214	2.4477	6.7121	2.4477E-03	68.4214	6.6806E-05	1.1230E-04
22	4.6207	2.2479	5.6510	2.2479E-03	57.6048	6.6865E-05	1.1240E-04
23	4.1686	2.0225	4.5572	2.0225E-03	46.4551	6.6991E-05	1.1261E-04
24	3.7720	1.8248	3.7114	1.8248E-03	37.8331	6.6976E-05	1.1259E-04
25	3.5134	1.6958	3.1993	1.6958E-03	32.6127	6.7039E-05	1.1269E-04



Pilot Experiment: Steel Round 12mm

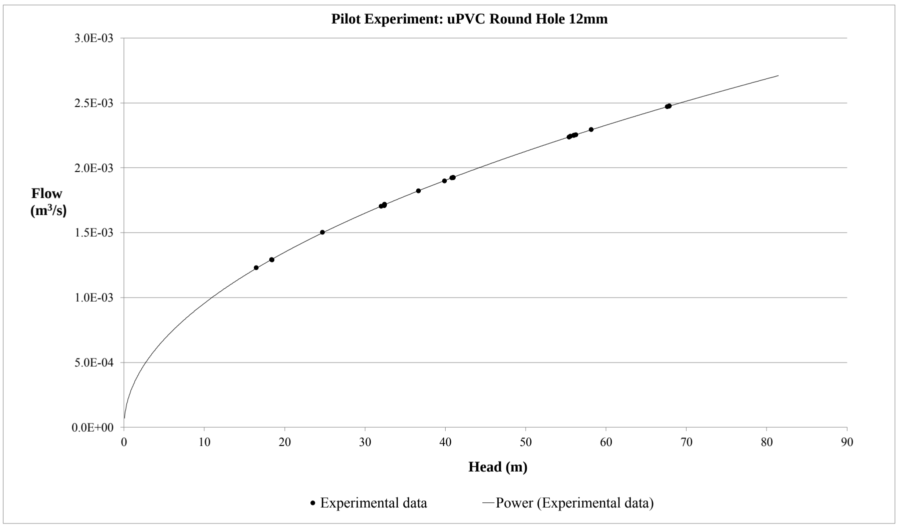




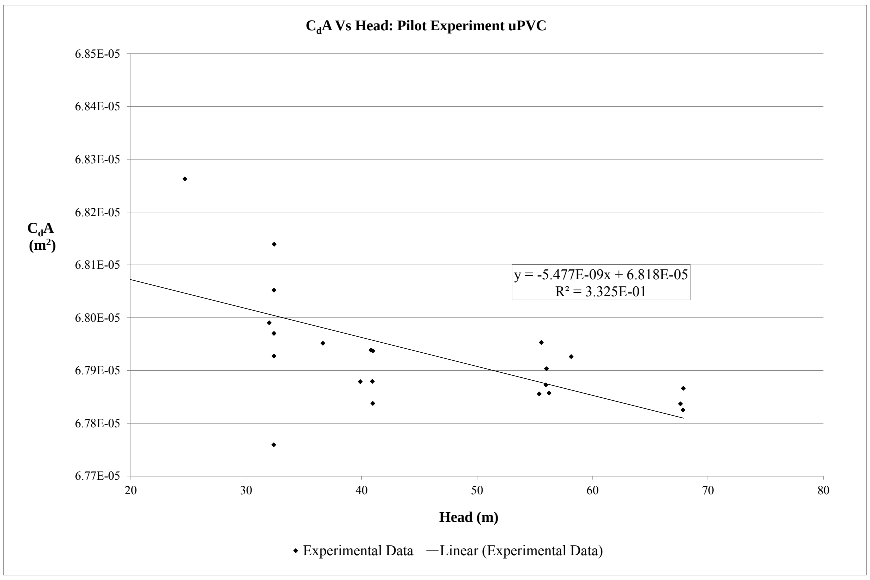
Pilot Experiment: uPVC Round 12mm

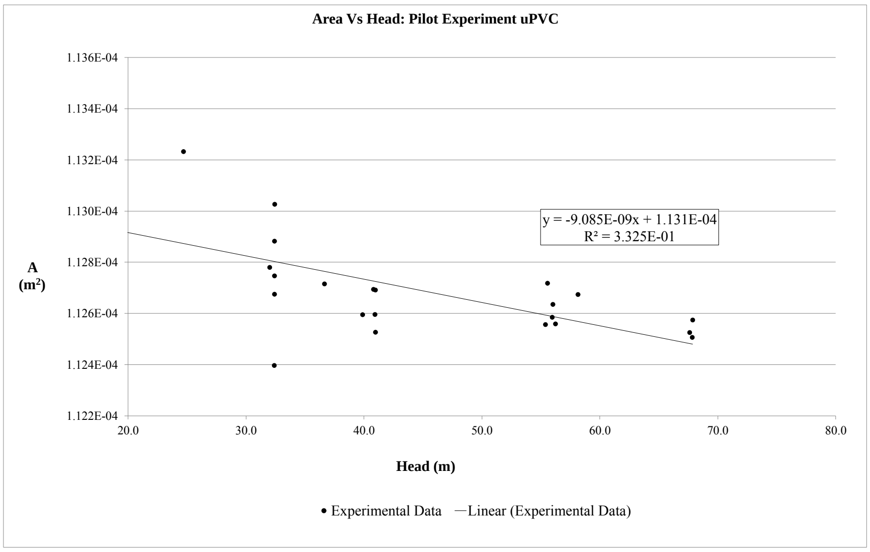
EXPERIMENTAL PARAMETERS	
1 Bar =	10.1937 m
1 l/s =	0.0010 m^3/s
g =	9.81 m/s^2
A_0 =	1.131E-04 m^2
N_1 PARAMETERS	
C =	3.047E-04
N1 =	0.4967
FAVAD PARAMETERS	
C_dA_0 =	6.818E-05 m^2
C_d=	0.6029
m =	-9.085E-09

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)
1	1.2899	1.8074	1.2899E-03	18.4241	6.7844E-05	1.1254E-04
2	1.7038	3.1400	1.7038E-03	32.0082	6.7990E-05	1.1278E-04
3	1.9237	4.0157	1.9237E-03	40.9349	6.7879E-05	1.1260E-04
4	2.2512	5.4957	2.2512E-03	56.0216	6.7903E-05	1.1264E-04
5	2.4709	6.6338	2.4709E-03	67.6228	6.7837E-05	1.1253E-04
6	2.2438	5.4514	2.2438E-03	55.5701	6.7953E-05	1.1272E-04
7	1.9262	4.0193	1.9262E-03	40.9716	6.7937E-05	1.1269E-04
8	1.7141	3.1800	1.7141E-03	32.4159	6.7970E-05	1.1275E-04
9	1.5026	2.4228	1.5026E-03	24.6968	6.8263E-05	1.1323E-04
10	1.7083	3.1779	1.7083E-03	32.3948	6.7759E-05	1.1240E-04
11	1.9235	4.0200	1.9235E-03	40.9786	6.7837E-05	1.1253E-04
12	2.2944	5.7048	2.2944E-03	58.1532	6.7926E-05	1.1267E-04
13	2.4745	6.6552	2.4745E-03	67.8407	6.7825E-05	1.1251E-04
14	2.2370	5.4343	2.2370E-03	55.3954	6.7855E-05	1.1256E-04
15	1.8222	3.5957	1.8222E-03	36.6536	6.7951E-05	1.1272E-04
16	1.7162	3.1800	1.7162E-03	32.4159	6.8052E-05	1.1288E-04
17	1.2297	1.6145	1.2297E-03	16.4575	6.8435E-05	1.1352E-04
18	1.7131	3.1800	1.7131E-03	32.4159	6.7927E-05	1.1268E-04
19	1.8989	3.9131	1.8989E-03	39.8889	6.7879E-05	1.1260E-04
20	2.2492	5.4907	2.2492E-03	55.9706	6.7873E-05	1.1259E-04
21	2.4766	6.6586	2.4766E-03	67.8758	6.7866E-05	1.1257E-04
22	2.2541	5.5172	2.2541E-03	56.2410	6.7857E-05	1.1256E-04
23	1.9224	4.0034	1.9224E-03	40.8099	6.7938E-05	1.1269E-04
24	1.7188	3.1814	1.7188E-03	32.4300	6.8139E-05	1.1303E-04
25	1.2924	1.8021	1.2924E-03	18.3705	6.8074E-05	1.1292E-04



Pilot Experiment: uPVC Round 12mm

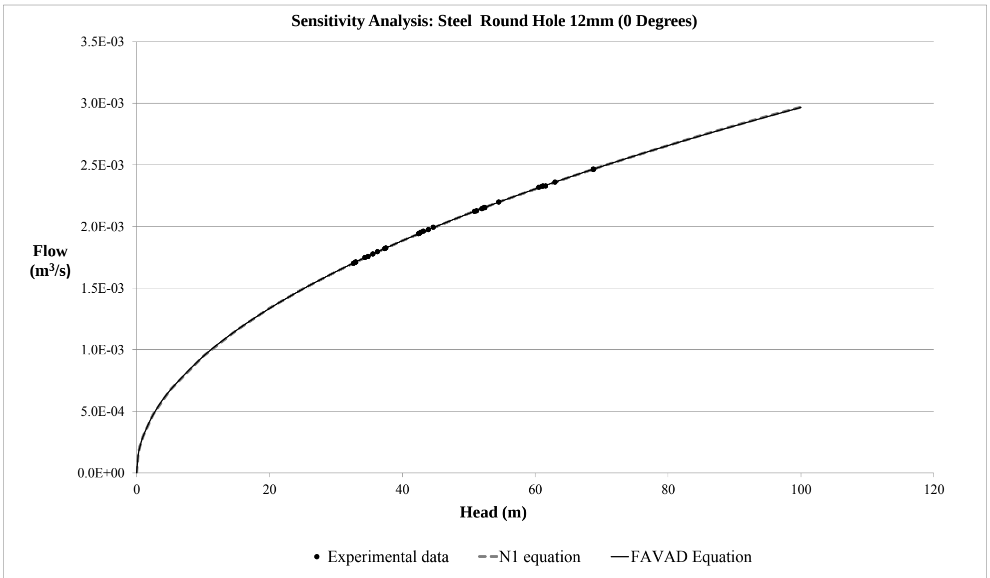




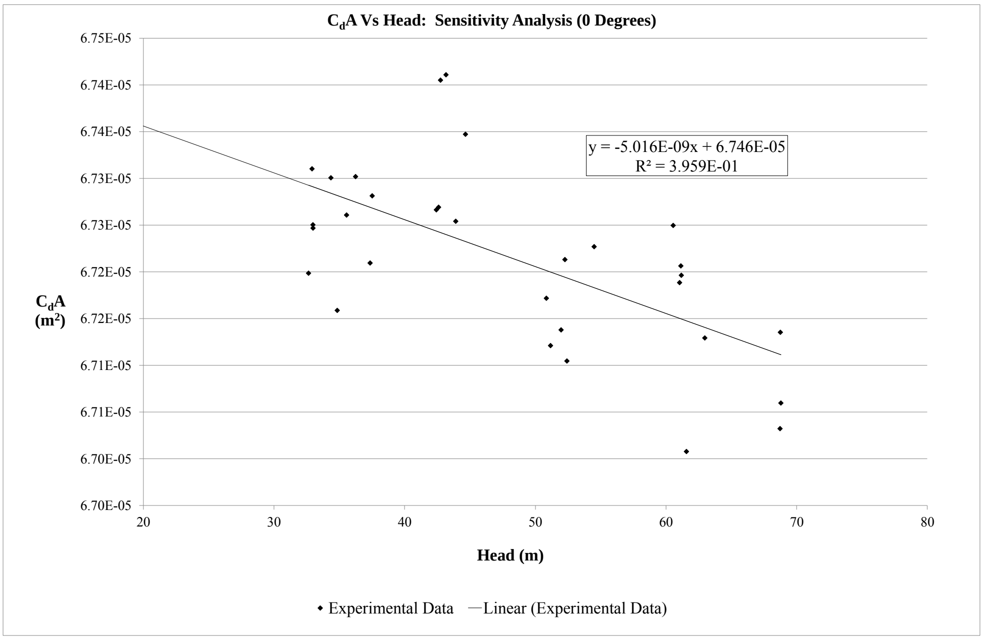
Sensitivity Analysis: Steel Round Hole 12mm (0 Degrees)

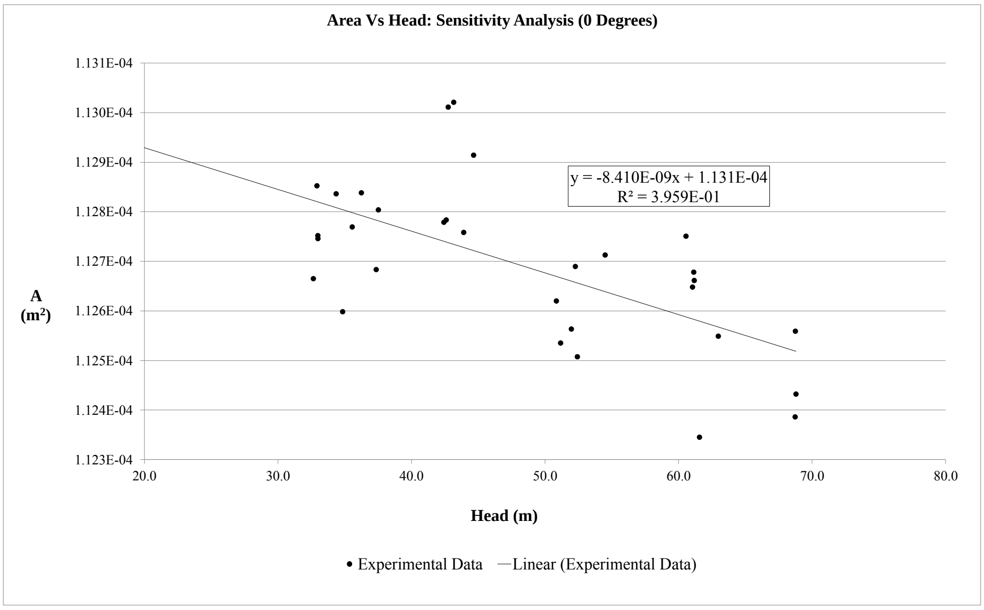
EXPERIMENTAL PARAMETERS	
1 Bar =	10.1937 m
1 l/s =	0.0010 m^3/s
g =	9.81 m/s^2
A_0 =	1.131E-04 m^2
N_1 PARAMETERS	
C =	3.017E-04
N1 =	0.4965
FAVAD PARAMETERS	
C_dA_0 =	6.746E-05 m^2
C_d =	0.5964
m =	-8.410E-09

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
1	1.7007	3.2028	1.7007E-03	32.6479	6.7198E-05	1.1266E-04	1.7031E-03	1.7031E-03
2	1.8196	3.6648	1.8196E-03	37.3581	6.7209E-05	1.1268E-04	1.8210E-03	1.8212E-03
3	1.9740	4.3076	1.9740E-03	43.9102	6.7254E-05	1.1276E-04	1.9731E-03	1.9735E-03
4	2.1521	5.1428	2.1521E-03	52.4236	6.7105E-05	1.1251E-04	2.1546E-03	2.1550E-03
5	2.3280	6.0014	2.3280E-03	61.1766	6.7196E-05	1.1266E-04	2.3263E-03	2.3264E-03
6	2.4616	6.7429	2.4616E-03	68.7345	6.7032E-05	1.1239E-04	2.4648E-03	2.4645E-03
7	2.3252	5.9883	2.3252E-03	61.0426	6.7188E-05	1.1265E-04	2.3238E-03	2.3239E-03
8	2.1525	5.1279	2.1525E-03	52.2717	6.7213E-05	1.1269E-04	2.1515E-03	2.1519E-03
9	1.9407	4.1621	1.9407E-03	42.4268	6.7266E-05	1.1278E-04	1.9397E-03	1.9401E-03
10	1.7766	3.4883	1.7766E-03	35.5584	6.7261E-05	1.1277E-04	1.7769E-03	1.7770E-03
11	1.7105	3.2290	1.7105E-03	32.9150	6.7310E-05	1.1285E-04	1.7100E-03	1.7100E-03
12	1.8255	3.6807	1.8255E-03	37.5198	6.7281E-05	1.1280E-04	1.8249E-03	1.8251E-03
13	1.9935	4.3807	1.9935E-03	44.6553	6.7347E-05	1.1291E-04	1.9897E-03	1.9901E-03
14	2.1984	5.3469	2.1984E-03	54.5046	6.7227E-05	1.1271E-04	2.1967E-03	2.1970E-03
15	2.3289	6.0400	2.3289E-03	61.5698	6.7008E-05	1.1235E-04	2.3337E-03	2.3338E-03
16	2.4658	6.7448	2.4658E-03	68.7546	6.7135E-05	1.1256E-04	2.4652E-03	2.4649E-03
17	2.3596	6.1779	2.3596E-03	62.9751	6.7129E-05	1.1255E-04	2.3600E-03	2.3600E-03
18	2.1439	5.0986	2.1439E-03	51.9737	6.7138E-05	1.1256E-04	2.1454E-03	2.1458E-03
19	1.9521	4.1938	1.9521E-03	42.7502	6.7405E-05	1.1301E-04	1.9471E-03	1.9474E-03
20	1.7948	3.5559	1.7948E-03	36.2473	6.7302E-05	1.1284E-04	1.7939E-03	1.7941E-03
21	1.7108	3.2359	1.7108E-03	32.9853	6.7250E-05	1.1275E-04	1.7118E-03	1.7119E-03
22	1.7559	3.4179	1.7559E-03	34.8413	6.7159E-05	1.1260E-04	1.7590E-03	1.7591E-03
23	1.9448	4.1793	1.9448E-03	42.6026	6.7269E-05	1.1278E-04	1.9437E-03	1.9441E-03
24	2.1217	4.9883	2.1217E-03	50.8489	6.7172E-05	1.1262E-04	2.1222E-03	2.1226E-03
25	2.3277	5.9979	2.3277E-03	61.1410	6.7206E-05	1.1268E-04	2.3256E-03	2.3257E-03
26	2.4637	6.7490	2.4637E-03	68.7968	6.7060E-05	1.1243E-04	2.4659E-03	2.4656E-03
27	2.3181	5.9407	2.3181E-03	60.5575	6.7250E-05	1.1275E-04	2.3146E-03	2.3147E-03
28	2.1266	5.0193	2.1266E-03	51.1652	6.7121E-05	1.1254E-04	2.1288E-03	2.1291E-03
29	1.9618	4.2345	1.9618E-03	43.1650	6.7411E-05	1.1302E-04	1.9564E-03	1.9568E-03
30	1.7474	3.3707	1.7474E-03	34.3595	6.7301E-05	1.1284E-04	1.7469E-03	1.7470E-03
31	1.7109	3.2367	1.7109E-03	32.9935	6.7247E-05	1.1275E-04	1.7120E-03	1.7121E-03



Sensitivity Analysis: Steel Round Hole 12mm (0 Degrees)

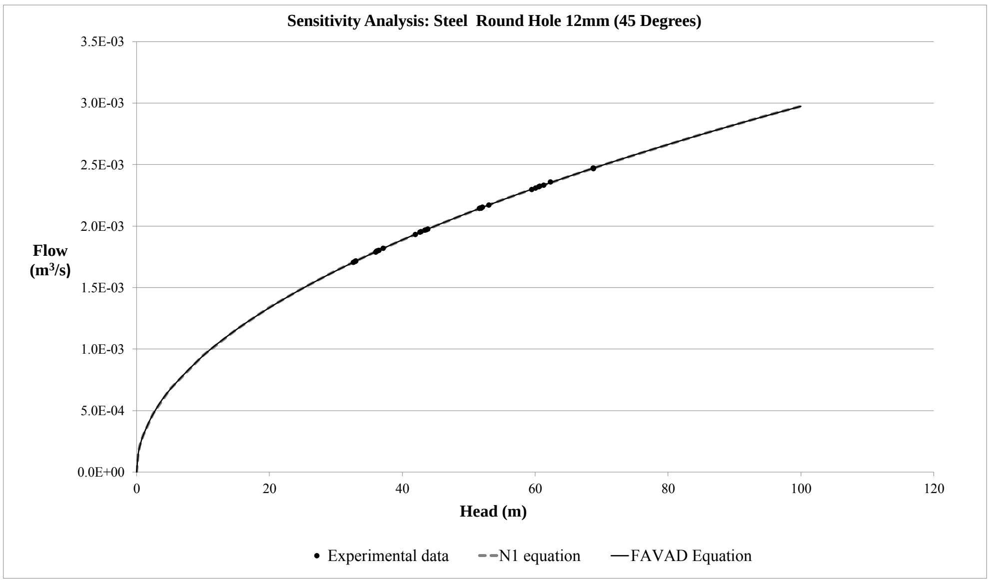




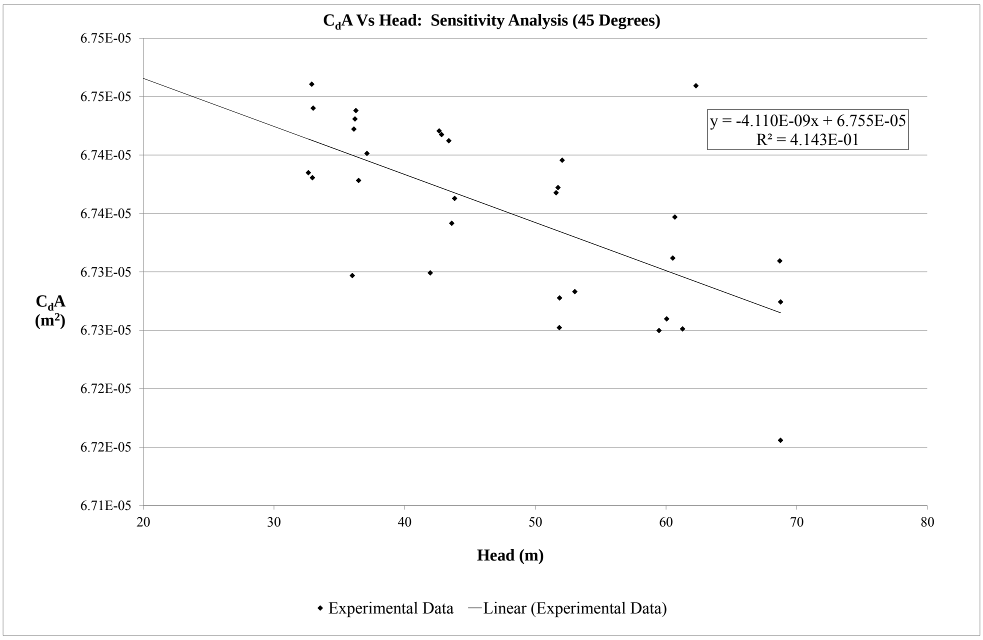
Sensitivity Analysis: Steel Round Hole 12mm (45 Degrees)

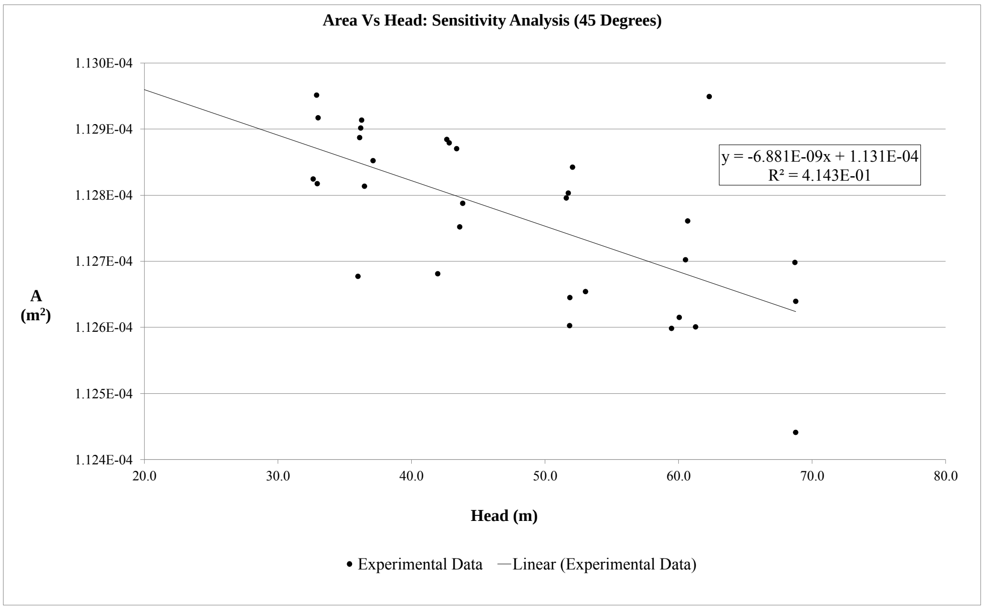
EXPERIMENTAL PARAMETERS		
1 Bar =	10.1937	m
1 l/s =	0.0010	m^3/s
g =	9.81	m/s^2
A_0 =	1.131E-04	m^2
N_1 PARAMETERS		
C =	3.025E-04	
N1 =	0.4964	
FAVAD PARAMETERS		
C_dA_0 =	6.755E-05	m^2
C_d =	0.5973	
m =	-6.881E-09	

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
1	1.7051	3.2014	1.7051E-03	32.6343	6.7385E-05	1.1282E-04	1.7064E-03	1.7058E-03
2	1.8026	3.5786	1.8026E-03	36.4793	6.7378E-05	1.1281E-04	1.8034E-03	1.8031E-03
3	1.9755	4.3000	1.9755E-03	43.8328	6.7363E-05	1.1279E-04	1.9755E-03	1.9756E-03
4	2.1434	5.0614	2.1434E-03	51.5941	6.7368E-05	1.1280E-04	2.1420E-03	2.1424E-03
5	2.3088	5.8914	2.3088E-03	60.0553	6.7260E-05	1.1262E-04	2.3097E-03	2.3102E-03
6	2.4714	6.7407	2.4714E-03	68.7124	6.7309E-05	1.1270E-04	2.4694E-03	2.4698E-03
7	2.3195	5.9371	2.3195E-03	60.5213	6.7312E-05	1.1270E-04	2.3186E-03	2.3191E-03
8	2.1703	5.2022	2.1703E-03	53.0298	6.7283E-05	1.1265E-04	2.1714E-03	2.1718E-03
9	1.9543	4.2014	1.9543E-03	42.8280	6.7417E-05	1.1288E-04	1.9529E-03	1.9529E-03
10	1.7947	3.5429	1.7947E-03	36.1148	6.7422E-05	1.1289E-04	1.7945E-03	1.7941E-03
11	1.7138	3.2269	1.7138E-03	32.8940	6.7461E-05	1.1295E-04	1.7132E-03	1.7126E-03
12	1.8189	3.6414	1.8189E-03	37.1191	6.7401E-05	1.1285E-04	1.8191E-03	1.8188E-03
13	1.9502	4.1834	1.9502E-03	42.6447	6.7421E-05	1.1288E-04	1.9488E-03	1.9488E-03
14	2.1466	5.0759	2.1466E-03	51.7417	6.7372E-05	1.1280E-04	2.1451E-03	2.1454E-03
15	2.3238	5.9531	2.3238E-03	60.6840	6.7347E-05	1.1276E-04	2.3217E-03	2.3222E-03
16	2.4668	6.7462	2.4668E-03	68.7687	6.7156E-05	1.1244E-04	2.4704E-03	2.4708E-03
17	2.2972	5.8345	2.2972E-03	59.4748	6.7250E-05	1.1260E-04	2.2986E-03	2.2991E-03
18	2.1448	5.0855	2.1448E-03	51.8401	6.7252E-05	1.1260E-04	2.1471E-03	2.1474E-03
19	1.9667	4.2559	1.9667E-03	43.3829	6.7412E-05	1.1287E-04	1.9654E-03	1.9655E-03
20	1.7970	3.5510	1.7970E-03	36.1981	6.7431E-05	1.1290E-04	1.7965E-03	1.7962E-03
21	1.7130	3.2317	1.7130E-03	32.9432	6.7381E-05	1.1282E-04	1.7144E-03	1.7138E-03
22	1.7989	3.5579	1.7989E-03	36.2677	6.7438E-05	1.1291E-04	1.7982E-03	1.7979E-03
23	1.9698	4.2779	1.9698E-03	43.6079	6.7342E-05	1.1275E-04	1.9705E-03	1.9706E-03
24	2.1461	5.0876	2.1461E-03	51.8612	6.7278E-05	1.1265E-04	2.1475E-03	2.1479E-03
25	2.3318	6.0110	2.3318E-03	61.2746	6.7251E-05	1.1260E-04	2.3329E-03	2.3333E-03
26	2.4712	6.7469	2.4712E-03	68.7757	6.7274E-05	1.1264E-04	2.4705E-03	2.4709E-03
27	2.3585	6.1114	2.3585E-03	62.2979	6.7459E-05	1.1295E-04	2.3522E-03	2.3526E-03
28	2.1539	5.1069	2.1539E-03	52.0581	6.7395E-05	1.1284E-04	2.1516E-03	2.1519E-03
29	1.9310	4.1166	1.9310E-03	41.9628	6.7299E-05	1.1268E-04	1.9332E-03	1.9332E-03
30	1.7884	3.5310	1.7884E-03	35.9942	6.7297E-05	1.1268E-04	1.7915E-03	1.7911E-03
31	1.7162	3.2379	1.7162E-03	33.0064	6.7440E-05	1.1292E-04	1.7161E-03	1.7155E-03



Sensitivity Analysis: Steel Round Hole 12mm (45 Degrees)

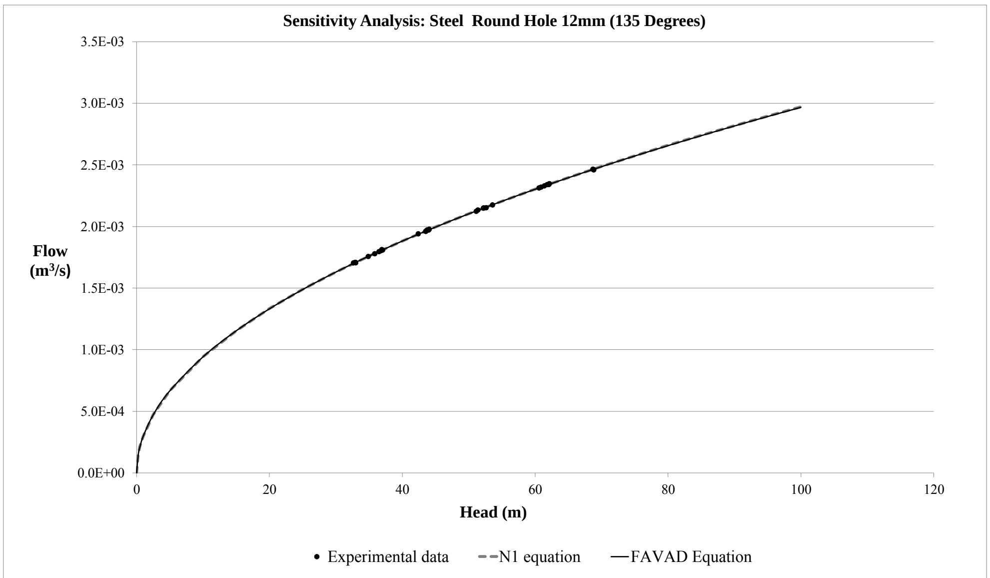




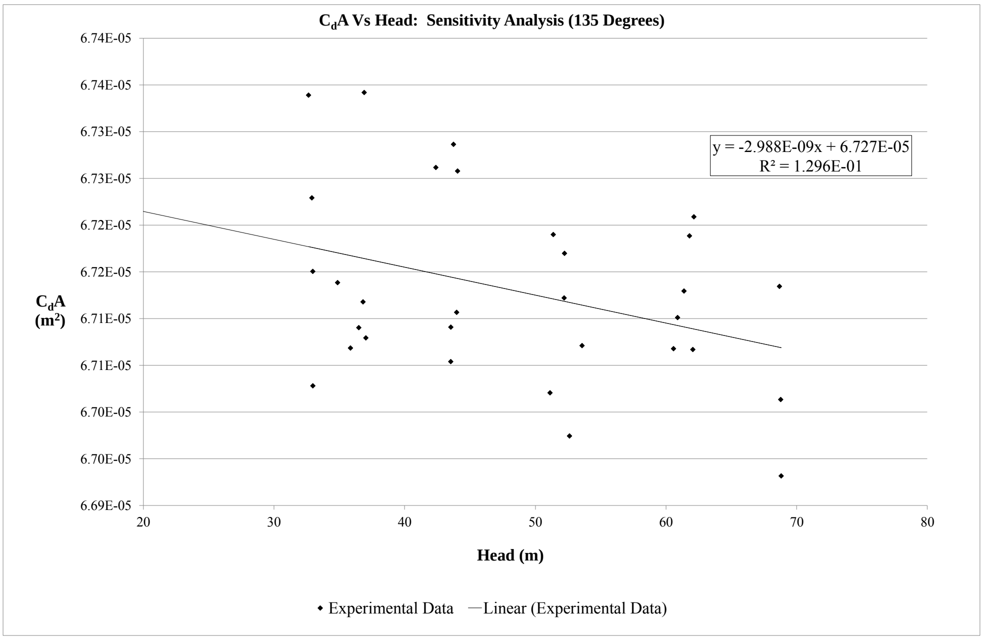
Sensitivity Analysis: Steel Round Hole 12mm (135 Degrees)

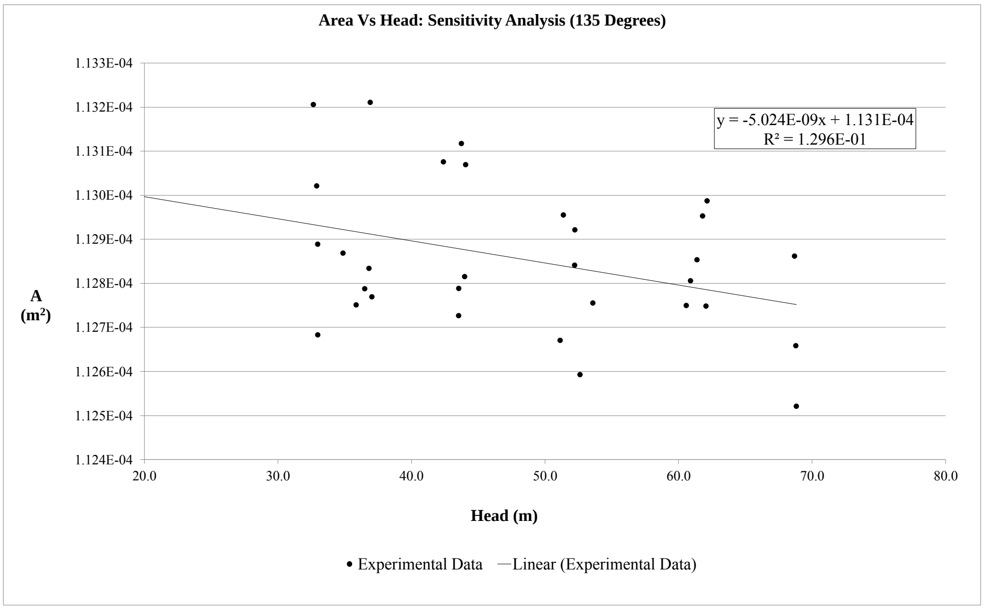
EXPERIMENTAL PARAMETERS	
1 Bar =	10.1937 m
1 l/s =	0.0010 m^3/s
g =	9.81 m/s^2
A_0 =	1.131E-04 m^2
N_1 PARAMETERS	
C =	2.996E-04
N1 =	0.4982
FAVAD PARAMETERS	
C_dA_0 =	6.727E-05 m^2
C_d =	0.5948
m =	-5.024E-09

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
1	1.7043	3.2027	1.7043E-03	32.6470	6.7339E-05	1.1321E-04	1.7009E-03	1.7002E-03
2	1.8122	3.6207	1.8122E-03	36.9082	6.7342E-05	1.1321E-04	1.8081E-03	1.8074E-03
3	1.9773	4.3214	1.9773E-03	44.0508	6.7258E-05	1.1307E-04	1.9747E-03	1.9739E-03
4	2.1332	5.0400	2.1332E-03	51.3761	6.7190E-05	1.1296E-04	2.1319E-03	2.1310E-03
5	2.3467	6.0957	2.3467E-03	62.1378	6.7209E-05	1.1299E-04	2.3438E-03	2.3425E-03
6	2.4645	6.7379	2.4645E-03	68.6843	6.7134E-05	1.1286E-04	2.4637E-03	2.4621E-03
7	2.3396	6.0628	2.3396E-03	61.8018	6.7188E-05	1.1295E-04	2.3375E-03	2.3362E-03
8	2.1503	5.1243	2.1503E-03	52.2353	6.7170E-05	1.1292E-04	2.1496E-03	2.1487E-03
9	1.9711	4.2907	1.9711E-03	43.7382	6.7286E-05	1.1312E-04	1.9677E-03	1.9669E-03
10	1.7561	3.4207	1.7561E-03	34.8694	6.7138E-05	1.1287E-04	1.7576E-03	1.7569E-03
11	1.7081	3.2276	1.7081E-03	32.9010	6.7229E-05	1.1302E-04	1.7074E-03	1.7067E-03
12	1.8039	3.6117	1.8039E-03	36.8168	6.7118E-05	1.1283E-04	1.8058E-03	1.8051E-03
13	1.9713	4.3145	1.9713E-03	43.9805	6.7107E-05	1.1282E-04	1.9731E-03	1.9723E-03
14	2.1227	5.0159	2.1227E-03	51.1301	6.7021E-05	1.1267E-04	2.1268E-03	2.1259E-03
15	2.3193	5.9736	2.3193E-03	60.8927	6.7101E-05	1.1281E-04	2.3203E-03	2.3190E-03
16	2.4618	6.7476	2.4618E-03	68.7827	6.7013E-05	1.1266E-04	2.4655E-03	2.4638E-03
17	2.3296	6.0214	2.3296E-03	61.3800	6.7129E-05	1.1285E-04	2.3295E-03	2.3282E-03
18	2.1484	5.1221	2.1484E-03	52.2135	6.7122E-05	1.1284E-04	2.1492E-03	2.1482E-03
19	1.9398	4.1586	1.9398E-03	42.3916	6.7262E-05	1.1308E-04	1.9372E-03	1.9365E-03
20	1.7788	3.5172	1.7788E-03	35.8536	6.7068E-05	1.1275E-04	1.7821E-03	1.7815E-03
21	1.7079	3.2345	1.7079E-03	32.9713	6.7150E-05	1.1289E-04	1.7093E-03	1.7086E-03
22	1.7952	3.5800	1.7952E-03	36.4934	6.7090E-05	1.1279E-04	1.7979E-03	1.7972E-03
23	1.9608	4.2707	1.9608E-03	43.5343	6.7091E-05	1.1279E-04	1.9631E-03	1.9623E-03
24	2.1520	5.1621	2.1520E-03	52.6205	6.6974E-05	1.1259E-04	2.1575E-03	2.1566E-03
25	2.3402	6.0876	2.3402E-03	62.0549	6.7067E-05	1.1275E-04	2.3422E-03	2.3409E-03
26	2.4594	6.7510	2.4594E-03	68.8179	6.6932E-05	1.1252E-04	2.4661E-03	2.4645E-03
27	2.3122	5.9428	2.3122E-03	60.5786	6.7068E-05	1.1275E-04	2.3143E-03	2.3131E-03
28	2.1747	5.2566	2.1747E-03	53.5836	6.7071E-05	1.1276E-04	2.1771E-03	2.1761E-03
29	1.9596	4.2703	1.9596E-03	43.5305	6.7054E-05	1.1273E-04	1.9630E-03	1.9623E-03
30	1.8081	3.6329	1.8081E-03	37.0322	6.7079E-05	1.1277E-04	1.8111E-03	1.8104E-03
31	1.7050	3.2352	1.7050E-03	32.9783	6.7028E-05	1.1268E-04	1.7094E-03	1.7087E-03



Sensitivity Analysis: Steel Round Hole 12mm (135 Degrees)

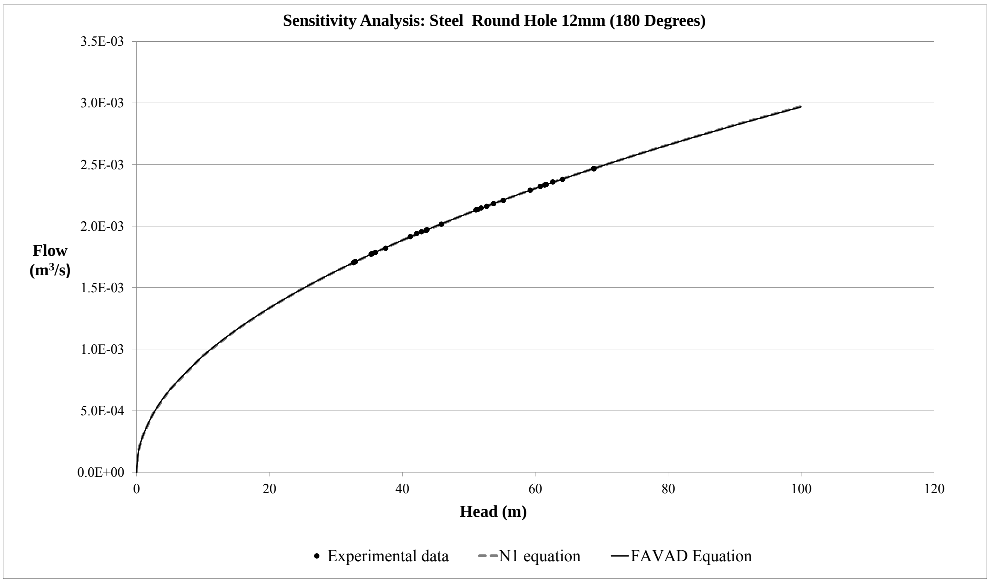




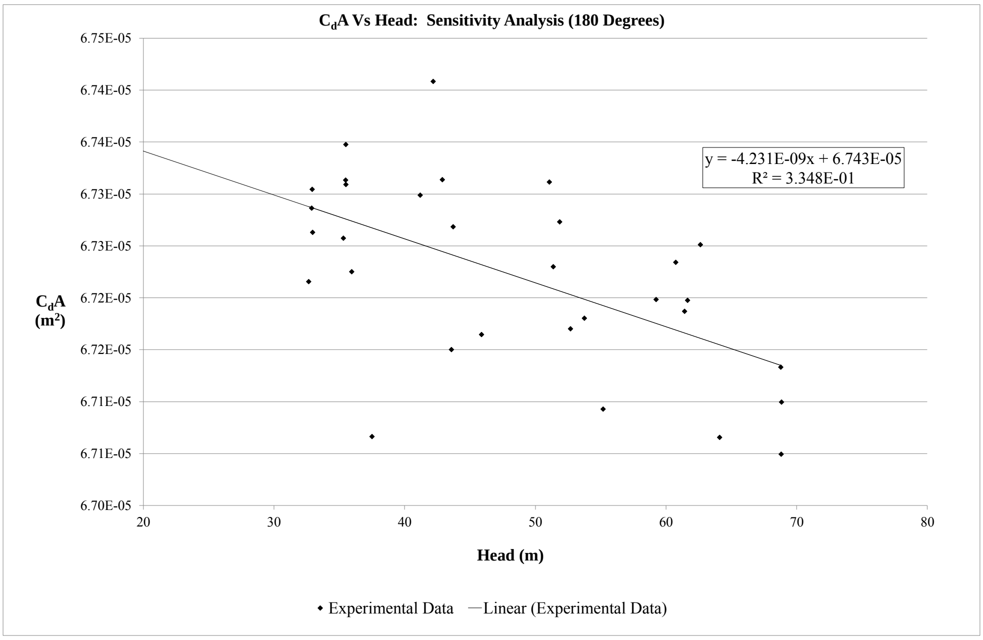
Sensitivity Analysis: Steel Round Hole 12mm (180 Degrees)

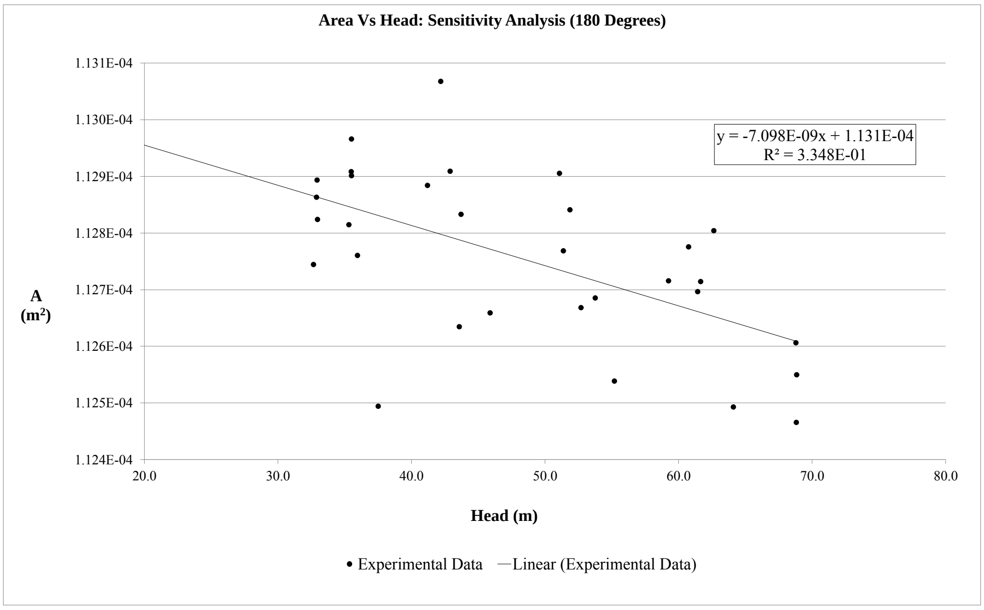
EXPERIMENTAL PARAMETERS	
1 Bar =	10.1937 m
1 l/s =	0.0010 m^3/s
g =	9.81 m/s^2
A_0 =	1.131E-04 m^2
N_1 PARAMETERS	
C =	3.010E-04
N1 =	0.4972
FAVAD PARAMETERS	
C_dA_0 =	6.743E-05 m^2
C_d =	0.5962
m =	-7.098E-09

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
1	1.7015	3.2040	1.7015E-03	32.6606	6.7216E-05	1.1274E-04	1.7032E-03	1.7033E-03
2	1.8193	3.6793	1.8193E-03	37.5057	6.7066E-05	1.1249E-04	1.8244E-03	1.8247E-03
3	2.0152	4.5014	2.0152E-03	45.8856	6.7165E-05	1.1266E-04	2.0168E-03	2.0173E-03
4	2.2078	5.4145	2.2078E-03	55.1935	6.7093E-05	1.1254E-04	2.2108E-03	2.2111E-03
5	2.3785	6.2890	2.3785E-03	64.1077	6.7066E-05	1.1249E-04	2.3816E-03	2.3817E-03
6	2.4663	6.7483	2.4663E-03	68.7898	6.7133E-05	1.1261E-04	2.4666E-03	2.4664E-03
7	2.3325	6.0262	2.3325E-03	61.4292	6.7187E-05	1.1270E-04	2.3316E-03	2.3318E-03
8	2.1345	5.0400	2.1345E-03	51.3761	6.7230E-05	1.1277E-04	2.1334E-03	2.1338E-03
9	1.9527	4.2076	1.9527E-03	42.8908	6.7314E-05	1.1291E-04	1.9503E-03	1.9507E-03
10	1.7704	3.4643	1.7704E-03	35.3138	6.7257E-05	1.1281E-04	1.7706E-03	1.7709E-03
11	1.7092	3.2262	1.7092E-03	32.8869	6.7286E-05	1.1286E-04	1.7090E-03	1.7092E-03
12	1.7854	3.5269	1.7854E-03	35.9521	6.7225E-05	1.1276E-04	1.7864E-03	1.7867E-03
13	1.9635	4.2752	1.9635E-03	43.5797	6.7150E-05	1.1263E-04	1.9658E-03	1.9662E-03
14	2.1818	5.2738	2.1818E-03	53.7594	6.7180E-05	1.1269E-04	2.1820E-03	2.1824E-03
15	2.3576	6.1448	2.3576E-03	62.6384	6.7251E-05	1.1280E-04	2.3543E-03	2.3544E-03
16	2.4637	6.7510	2.4637E-03	68.8179	6.7049E-05	1.1247E-04	2.4671E-03	2.4669E-03
17	2.2911	5.8124	2.2911E-03	59.2499	6.7198E-05	1.1272E-04	2.2901E-03	2.2904E-03
18	2.1309	5.0110	2.1309E-03	51.0809	6.7311E-05	1.1291E-04	2.1273E-03	2.1277E-03
19	1.9393	4.1386	1.9393E-03	42.1878	6.7408E-05	1.1307E-04	1.9343E-03	1.9347E-03
20	1.7775	3.4828	1.7775E-03	35.5021	6.7348E-05	1.1297E-04	1.7753E-03	1.7756E-03
21	1.7105	3.2333	1.7105E-03	32.9596	6.7263E-05	1.1282E-04	1.7109E-03	1.7111E-03
22	1.7765	3.4829	1.7765E-03	35.5031	6.7309E-05	1.1290E-04	1.7753E-03	1.7756E-03
23	1.9700	4.2883	1.9700E-03	43.7133	6.7268E-05	1.1283E-04	1.9688E-03	1.9692E-03
24	2.1598	5.1697	2.1598E-03	52.6978	6.7170E-05	1.1267E-04	2.1605E-03	2.1609E-03
25	2.3371	6.0483	2.3371E-03	61.6542	6.7198E-05	1.1271E-04	2.3359E-03	2.3360E-03
26	2.4661	6.7538	2.4661E-03	68.8460	6.7100E-05	1.1255E-04	2.4676E-03	2.4674E-03
27	2.3213	5.9600	2.3213E-03	60.7543	6.7234E-05	1.1278E-04	2.3188E-03	2.3190E-03
28	2.1461	5.0883	2.1461E-03	51.8683	6.7273E-05	1.1284E-04	2.1435E-03	2.1439E-03
29	1.9133	4.0414	1.9133E-03	41.1965	6.7299E-05	1.1288E-04	1.9116E-03	1.9120E-03
30	1.7762	3.4814	1.7762E-03	35.4881	6.7313E-05	1.1291E-04	1.7749E-03	1.7752E-03
31	1.7107	3.2303	1.7107E-03	32.9291	6.7304E-05	1.1289E-04	1.7101E-03	1.7103E-03



Sensitivity Analysis: Steel Round Hole 12mm (180 Degrees)





APPENDIX C:
Python Programme Design

Data Analysis Code with Explanation and Example Output

In the following any text inside three inverted commas (""") or preceded by a hash (#) is a comment and does not affect the code. These comments are an explanation of what the code does.

In [48]: import numpy as np import sys

"""The following variable online is set to true for running this code online , set the variable to false to run on a local PC.

In the case you are running this code on a PC you must set online = False and run the command python data_analysis.py [file_name], with the [file_name] replaced with the name of the file you would like to analyse""" online = True if online == True:

file_name="cdlwin4_export_pressure_mPVC_long_50mm.csv" elif (len(sys.argv) > 1): file_name = sys.argv[1] #Here we are getting the name of the file from the command line, else: print "No file name, remember to add a filename to your run" exit()

data = np.genfromtxt(file_name, delimiter=',', skip_header=1) #This opens the file and reads in the data

data = data[:,1] #This selects the numerical values from the csv file (the first row contains times which we do not need yet)

print "THE DATA\n %s\n"%str(data[:100]) # Print out the first 100 data value s

print "Data dimensions = %s\n"%str(data.shape) #Print out the dimensions of the data

In the above section the data is accessed from the file and stored in the data variable. Some of the data has been printed to show that it worked and the dimensions have also been printed out of the data to show that all the data was accessed.

THE DATA

[0.34 0.34 0.34 0.34 0.34 0.34 0.34 0.34 3.36 3.94 3.92 3.92

3.9 3.9 3.9 3.9 3.9 3.88 3.88 3.9 3.88 3.88 3.88 3.88 3.88 3.88 3.88 3.88 3.86 3.86 3.86 3.86 3.86 3.86 3.86 3.86 3.86 3.86 3.86 4.18 4.2 4.18 4.2 4.18 4.18 4.18 4.18 4.18 4.18 4.18 4.18 4.16 4.16 4.16 4.16 4.16 4.16 4.16 4.16 4.16

4.16 4.16 4.16 4.16 4.16 4.14 4.16 4.14 4.14 4.66 4.68 4.66 4.66 4.66 4.64 4.64 4.64 4.62 4.62 4.62 4.62 4.6 4.6 4.6

4.6 4.6 4.6 4.6 4.6 4.58 4.58 4.58 4.58 4.58 4.58 4.58

4.56 4.56 4.56 5.14]

Data dimensions = (953,)

In [27]: """Each value is subtracted from the previous value in the data to get the difference between the values. The following is an example of the np.roll method to show how it works."""

example_data = np.array([0,1,2,3,4,5]) #Made example data containing the lis t of numbers 0,1,2,3,4,5

rolled_example_data = np.roll(example_data, 1) # The data has now been rolled, the rolled_example_data should contain the same values moved by one place in the new order 5,0,1,2,3,4

diff=np.abs(example_data - rolled_example_data) # The rolled data is then subtracted from the example data

print "example_data = \t\t%s\n"%str(example_data) print "rolled_example_data =\t %s\n"%str(rolled_example_data) print "The difference =\t%s\n"%str(diff)

In [46]: """The same process is done to the data and print out the first 100 differences from our actual data""" diff = np.abs(data - numpy.roll(data, 1)) print "The differences :\n%s"%str(diff[0:100])

You can see that the values above are mainly very small these sections are likely to be part of the same run. At the points where the pressure was changed, you see a much larger difference.

In [36]: print "Standard Deviation = %s"%str(np.std(diff)) #The standard deviation of the differences is calculated and printed out

print "Median = %s"%str(np.median(diff)) # Here the median value of the difference is calculated and printed out

threshold = np.std(diff) + np.median(diff) # Here the standard deviation is added to the median value and put it in the variable threshold print "Threshold = %f"%threshold # Here the threshold is printed out

example_data = [0 1 2 3 4 5] rolled_example_data = [5 0 1 2 3 4] The difference = [5 1 1 1 1 1]

The differences :

[0.34 0. 0. 0. 0. 0. 0. 0. 3.02 0.58 0.02 0.

0.02 0. 0. 0. 0. 0.02 0. 0.02 0.02 0. 0. 0. 0. 0. 0. 0. 0.02 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.32 0.02 0.02 0.02 0.02 0. 0. 0. 0. 0. 0. 0. 0.02 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0. 0.

0. 0.02 0.02 0.02 0. 0.52 0.02 0.02 0. 0. 0.02 0. 0.

0.02 0. 0. 0. 0.02 0. 0. 0. 0. 0. 0. 0.

0.02 0. 0. 0. 0. 0. 0. 0.02 0. 0. 0.58]

Standard Deviation = 0.161999618717

Median = 0.0

Threshold = 0.162000

The standard deviation tells us where two thirds of the difference values will be. This is added to the median value to remove the inherent randomness in between values in each pressure run. In the cases where the difference between pressure runs is large and the internal variation is small, this threshold should allow us to see where the pressure was changed and where the pressure was held constant. Differences above this threshold are assumed to occur because the pressure was changed. The next step is to use this information to separate our data into separate pressure runs.

In [39]: indices = np.where(diff > threshold)[0] # Here each position where the difference is greater than the threshold is calculated print "Indices of pressure changes:\n%s\n"%str(indices)

The next step is to calculate the mean values in between these indices.

In [43]: times = np.genfromtxt('cdlwin4_export_pressure_mPVC_long_50mm.csv', delimite r=',', dtype=None) #Loading the data again to get the times

times = times[:,0] #Selecting the time values and saving them in the times variable

for i in range(indices.shape[0] - 1): #Creating a loop which will run from i = 0 to i = number of indices - 1

#all of the code following will be repeated until we get to the end of the list of indices

if indices[i+1] - indices[i] - 1 > 0: #If the indices are separated by at least 1 value (no point calculating the mean of 0 numbers)

segment = data[indices[i]+1:indices[i+1]] #Here I select the data between the two indices

print """From %s to %s, %i seconds. Mean = %f"""%(#Print out the following data times[indices[i]+1], #The time at the ith index times[indices[i+1]], #The time at the (i+1)th index

indices[i+1] - indices[i] - 1, #The difference between the indices (i.e. number of seconds in the segment)

np.mean(segment)) #The mean of the segment

Indices of pressure changes:

[0 8 9 39 69 99 128 158 188 218 248 279 308 338 367 396 426 456

486 516 546 576 606 636 666 696 726 756 786 787 816 846 876 906 936]

And finally, below is the mean value for each of the different runs. This code should work well unless the differences between pressure runs are of a similar size as the differences between values of the same pressure run.

In []:

From 15:02:34 to 15:02:41, 7 seconds. Mean = 0.340000

From 15:02:43 to 15:03:12, 29 seconds. Mean = 3.879310

From 15:03:13 to 15:03:42, 29 seconds. Mean = 4.166897

From 15:03:43 to 15:04:12, 29 seconds. Mean = 4.606897

From 15:04:13 to 15:04:41, 28 seconds. Mean = 4.982857

From 15:04:42 to 15:05:11, 29 seconds. Mean = 5.286207

From 15:05:12 to 15:05:41, 29 seconds. Mean = 5.461379

From 15:05:42 to 15:06:11, 29 seconds. Mean = 4.958621

From 15:06:12 to 15:06:41, 29 seconds. Mean = 4.519310

From 15:06:42 to 15:07:12, 30 seconds. Mean = 3.959333

From 15:07:13 to 15:07:41, 28 seconds. Mean = 3.466429

From 15:07:42 to 15:08:11, 29 seconds. Mean = 3.281379

From 15:08:12 to 15:08:40, 28 seconds. Mean = 3.520000

From 15:08:41 to 15:09:09, 28 seconds. Mean = 3.980714

From 15:09:10 to 15:09:39, 29 seconds. Mean = 4.535172

From 15:09:40 to 15:10:09, 29 seconds. Mean = 5.055862

From 15:10:10 to 15:10:39, 29 seconds. Mean = 5.314483

From 15:10:40 to 15:11:09, 29 seconds. Mean = 4.874483

From 15:11:10 to 15:11:39, 29 seconds. Mean = 4.399310

From 15:11:40 to 15:12:09, 29 seconds. Mean = 3.938621

From 15:12:10 to 15:12:39, 29 seconds. Mean = 3.455862

From 15:12:40 to 15:13:09, 29 seconds. Mean = 3.196552

From 15:13:10 to 15:13:39, 29 seconds. Mean = 3.460690

From 15:13:40 to 15:14:09, 29 seconds. Mean = 4.022069

From 15:14:10 to 15:14:39, 29 seconds. Mean = 4.532414

From 15:14:40 to 15:15:09, 29 seconds. Mean = 4.970345

From 15:15:10 to 15:15:39, 29 seconds. Mean = 5.248966

From 15:15:41 to 15:16:09, 28 seconds. Mean = 4.822143

From 15:16:10 to 15:16:39, 29 seconds. Mean = 4.323448

From 15:16:40 to 15:17:09, 29 seconds. Mean = 3.826897

From 15:17:10 to 15:17:39, 29 seconds. Mean = 3.362069

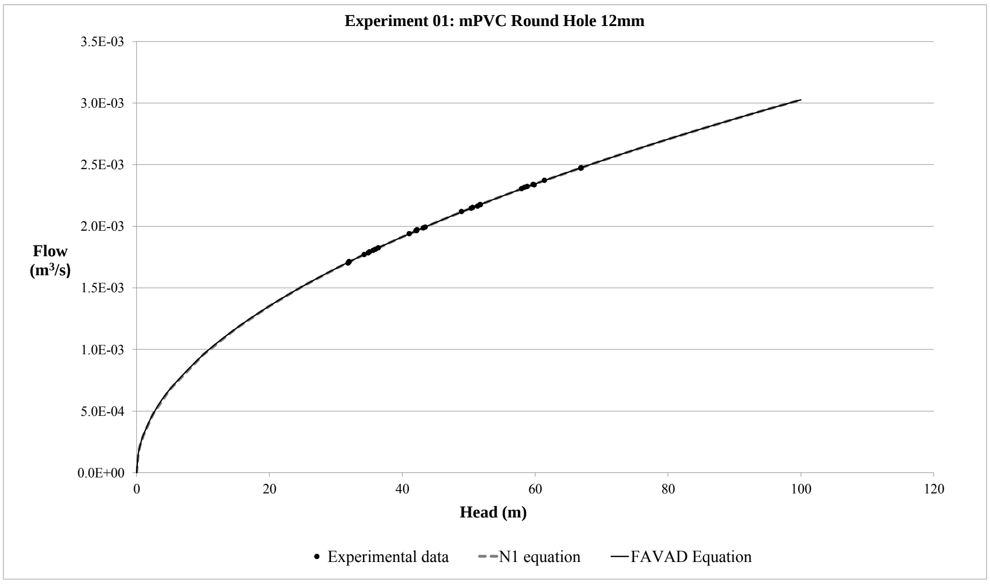
From 15:17:40 to 15:18:09, 29 seconds. Mean = 3.160000

APPENDIX D:
Experimental Results

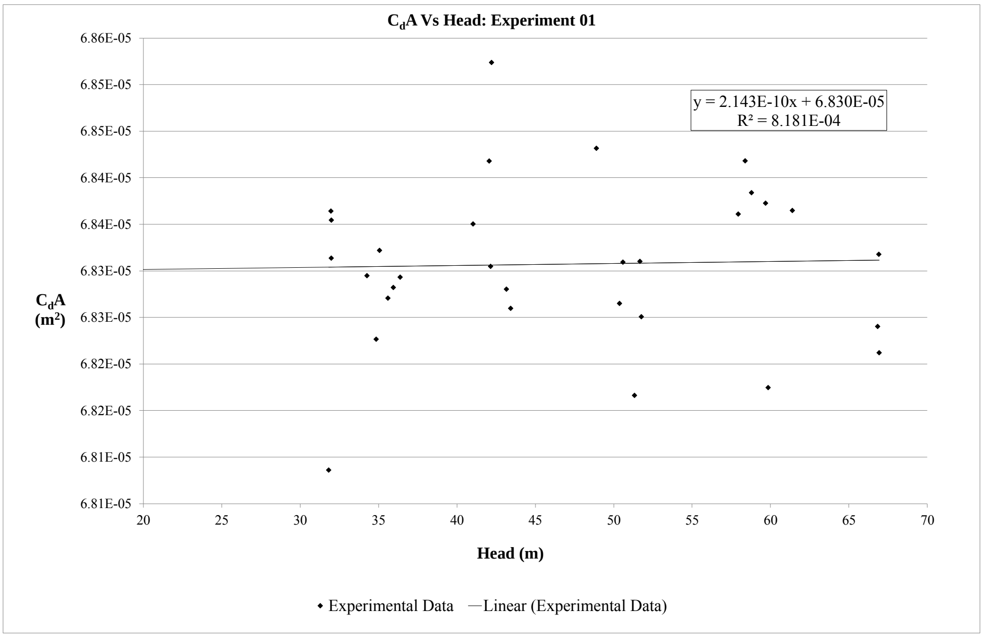
Experiment 01: mPVC Round 12mm

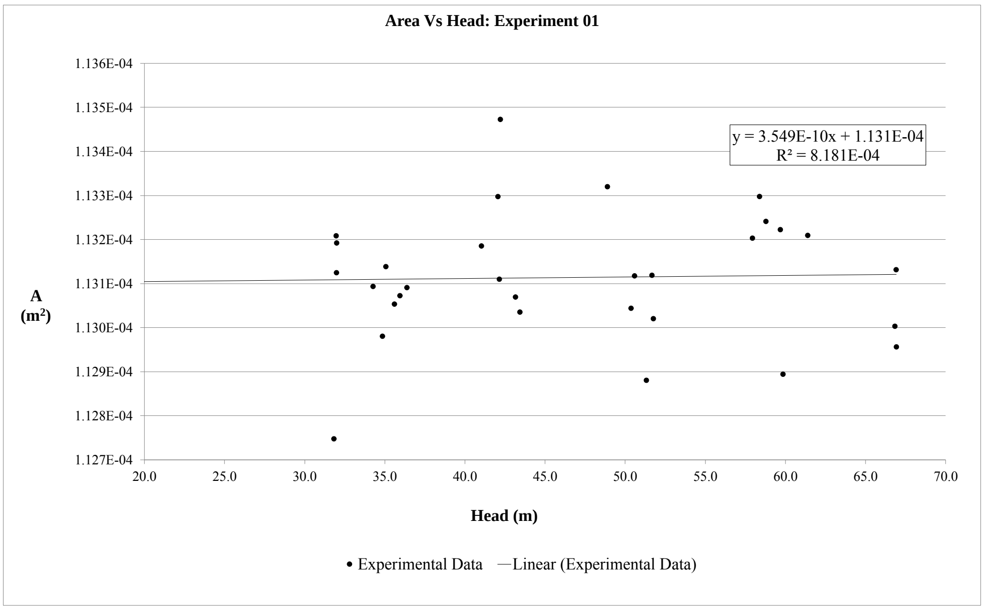
EXPERIMENTAL PARAMETERS	
1 Bar =	10.1937 m
1 l/s =	0.0010 m^3/s
g =	9.81 m/s^2
A_0 =	1.131E-04 m^2
N1 PARAMETERS	
C =	3.022E-04
N1 =	0.5003
R^2 =	0.99990
SSE =	2.665E-04
FAVAD PARAMETERS	
C_dA_0 =	6.830E-05 m^2
C_d =	0.6039
m =	3.549E-10
R^2 =	0.99990
SSE =	2.664E-04

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
1	1.7013	3.1220	1.7013E-03	31.8247	6.8086E-05	1.1275E-04	1.7067E-03	1.7068E-03
2	1.8133	3.5262	1.8133E-03	35.9450	6.8282E-05	1.1307E-04	1.8139E-03	1.8139E-03
3	1.9869	4.2338	1.9869E-03	43.1579	6.8280E-05	1.1307E-04	1.9876E-03	1.9877E-03
4	2.1750	5.0779	2.1750E-03	51.7621	6.8251E-05	1.1302E-04	2.1769E-03	2.1768E-03
5	2.3157	5.7279	2.3157E-03	58.3879	6.8418E-05	1.1330E-04	2.3121E-03	2.3120E-03
6	2.4711	6.5566	2.4711E-03	66.8354	6.8240E-05	1.1300E-04	2.4738E-03	2.4737E-03
7	2.3049	5.6843	2.3049E-03	57.9438	6.8361E-05	1.1320E-04	2.3033E-03	2.3032E-03
8	2.1195	4.7966	2.1195E-03	48.8945	6.8432E-05	1.1332E-04	2.1157E-03	2.1157E-03
9	1.9393	4.0250	1.9393E-03	41.0296	6.8350E-05	1.1319E-04	1.9380E-03	1.9380E-03
10	1.7842	3.4193	1.7842E-03	34.8554	6.8227E-05	1.1298E-04	1.7861E-03	1.7862E-03
11	1.7121	3.1359	1.7121E-03	31.9660	6.8364E-05	1.1321E-04	1.7105E-03	1.7106E-03
12	1.8246	3.5690	1.8246E-03	36.3809	6.8293E-05	1.1309E-04	1.8248E-03	1.8249E-03
13	1.9926	4.2607	1.9926E-03	43.4321	6.8260E-05	1.1304E-04	1.9940E-03	1.9940E-03
14	2.1751	5.0693	2.1751E-03	51.6747	6.8310E-05	1.1312E-04	2.1750E-03	2.1750E-03
15	2.3727	6.0228	2.3727E-03	61.3941	6.8365E-05	1.1321E-04	2.3709E-03	2.3708E-03
16	2.4753	6.5640	2.4753E-03	66.9113	6.8318E-05	1.1313E-04	2.4752E-03	2.4751E-03
17	2.3397	5.8552	2.3397E-03	59.6858	6.8373E-05	1.1322E-04	2.3377E-03	2.3376E-03
18	2.1521	4.9629	2.1521E-03	50.5898	6.8309E-05	1.1312E-04	2.1521E-03	2.1520E-03
19	1.9643	4.1350	1.9643E-03	42.1509	6.8305E-05	1.1311E-04	1.9643E-03	1.9643E-03
20	1.7921	3.4400	1.7921E-03	35.0663	6.8322E-05	1.1314E-04	1.7915E-03	1.7916E-03
21	1.7126	3.1386	1.7126E-03	31.9941	6.8354E-05	1.1319E-04	1.7112E-03	1.7113E-03
22	1.8043	3.4924	1.8043E-03	35.6005	6.8271E-05	1.1305E-04	1.8052E-03	1.8052E-03
23	1.9719	4.1407	1.9719E-03	42.2091	6.8524E-05	1.1347E-04	1.9657E-03	1.9657E-03
24	2.1632	5.0352	2.1632E-03	51.3269	6.8166E-05	1.1288E-04	2.1677E-03	2.1677E-03
25	2.3362	5.8713	2.3362E-03	59.8505	6.8175E-05	1.1289E-04	2.3409E-03	2.3408E-03
26	2.4718	6.5657	2.4718E-03	66.9288	6.8212E-05	1.1296E-04	2.4755E-03	2.4754E-03
27	2.3225	5.7671	2.3225E-03	58.7884	6.8384E-05	1.1324E-04	2.3200E-03	2.3199E-03
28	2.1460	4.9414	2.1460E-03	50.3713	6.8265E-05	1.1304E-04	2.1474E-03	2.1474E-03
29	1.9654	4.1262	1.9654E-03	42.0612	6.8418E-05	1.1330E-04	1.9622E-03	1.9622E-03
30	1.7708	3.3614	1.7708E-03	34.2648	6.8295E-05	1.1309E-04	1.7709E-03	1.7710E-03
31	1.7114	3.1379	1.7114E-03	31.9871	6.8314E-05	1.1312E-04	1.7110E-03	1.7111E-03



Experiment 01: mPVC Round 12mm

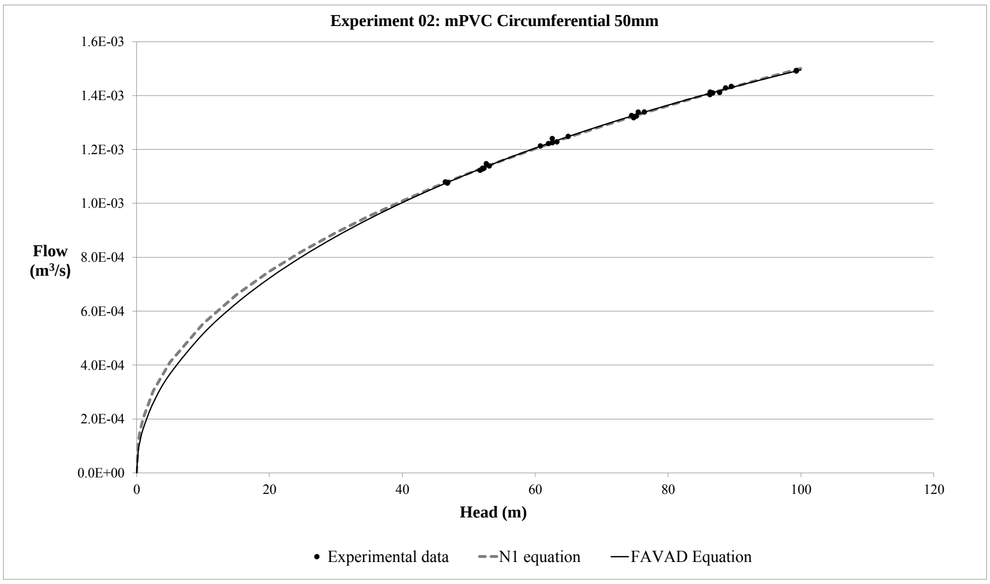




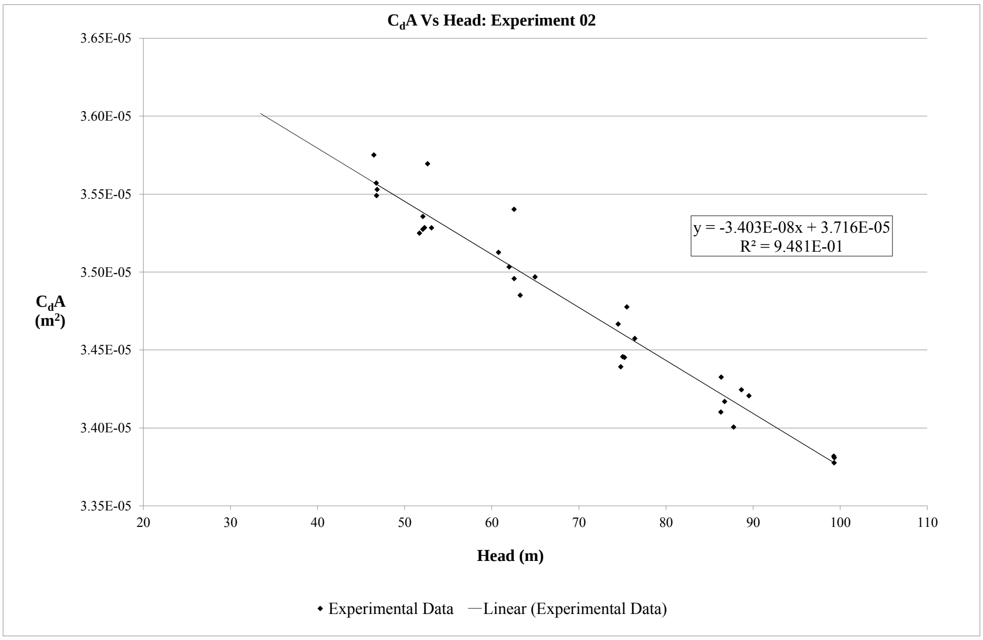
Experiment 02: mPVC Circumferential 50mm

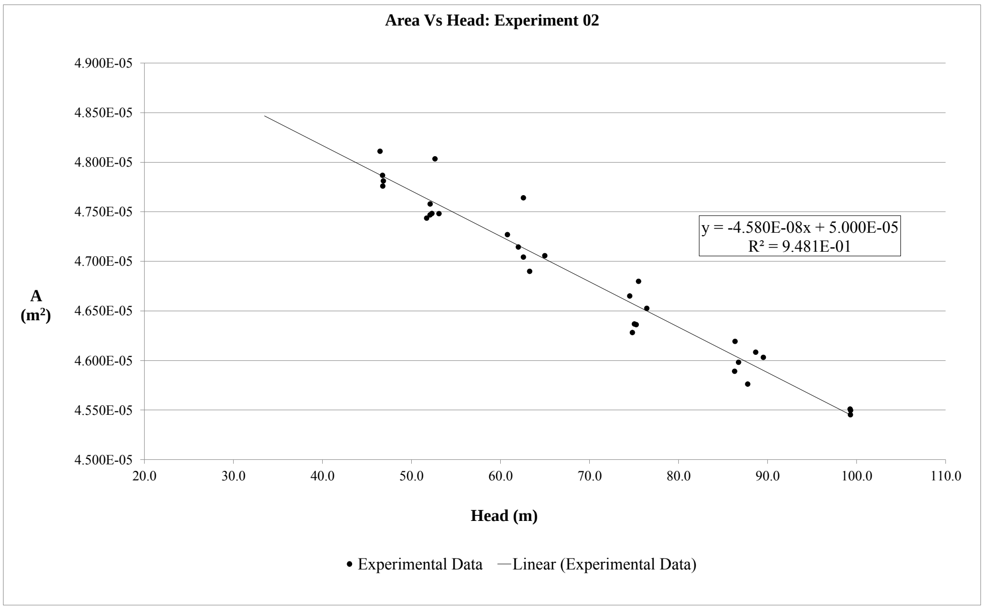
EXPERIMENTAL PARAMETERS		
1 Bar =	10.1937	m
1 l/s =	0.0010	m^3/s
g =	9.81	m/s^2
A_0 =	5.000E-05	m^2
N1 PARAMETERS		
C =	2.045E-04	
N1 =	0.4328	
R^2 =	0.99854	
SSE =	1.014E-04	
FAVAD PARAMETERS		
C_dA_0 =	3.716E-05	m^2
C_d =	0.7431	
m =	-4.580E-08	
R^2 =	0.99873	
SSE =	1.014E-04	

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
1	1.0795	4.5586	1.0795E-03	46.4686	3.5751E-05	4.8109E-05	1.0769E-03	1.0742E-03
2	1.1471	5.1641	1.1471E-03	52.6416	3.5694E-05	4.8033E-05	1.1367E-03	1.1365E-03
3	1.2404	6.1379	1.2404E-03	62.5681	3.5402E-05	4.7640E-05	1.2249E-03	1.2272E-03
4	1.3386	7.4076	1.3386E-03	75.5106	3.4776E-05	4.6798E-05	1.3288E-03	1.3312E-03
5	1.4283	8.6979	1.4283E-03	88.6639	3.4245E-05	4.6083E-05	1.4244E-03	1.4238E-03
6	1.4909	9.7421	1.4909E-03	99.3083	3.3776E-05	4.5453E-05	1.4960E-03	1.4909E-03
7	1.4096	8.5089	1.4096E-03	86.7369	3.4169E-05	4.5981E-05	1.4109E-03	1.4110E-03
8	1.3177	7.3393	1.3177E-03	74.8143	3.4392E-05	4.6281E-05	1.3234E-03	1.3260E-03
9	1.2219	6.0821	1.2219E-03	61.9987	3.5033E-05	4.7144E-05	1.2201E-03	1.2223E-03
10	1.1302	5.1297	1.1302E-03	52.2901	3.5285E-05	4.7482E-05	1.1334E-03	1.1331E-03
11	1.0772	4.5855	1.0772E-03	46.7433	3.5571E-05	4.7867E-05	1.0797E-03	1.0770E-03
12	1.1303	5.1103	1.1303E-03	52.0932	3.5356E-05	4.7578E-05	1.1315E-03	1.1312E-03
13	1.2130	5.9621	1.2130E-03	60.7754	3.5126E-05	4.7269E-05	1.2096E-03	1.2116E-03
14	1.3255	7.3100	1.3255E-03	74.5158	3.4666E-05	4.6650E-05	1.3212E-03	1.3237E-03
15	1.4128	8.4703	1.4128E-03	86.3440	3.4326E-05	4.6192E-05	1.4081E-03	1.4083E-03
16	1.4925	9.7386	1.4925E-03	99.2724	3.3819E-05	4.5510E-05	1.4958E-03	1.4907E-03
17	1.4033	8.4662	1.4033E-03	86.3018	3.4102E-05	4.5890E-05	1.4078E-03	1.4081E-03
18	1.3221	7.3614	1.3221E-03	75.0395	3.4457E-05	4.6368E-05	1.3252E-03	1.3277E-03
19	1.2249	6.1386	1.2249E-03	62.5751	3.4958E-05	4.7042E-05	1.2250E-03	1.2273E-03
20	1.1227	5.0724	1.1227E-03	51.7066	3.5250E-05	4.7435E-05	1.1279E-03	1.1274E-03
21	1.0752	4.5890	1.0752E-03	46.7784	3.5491E-05	4.7759E-05	1.0800E-03	1.0774E-03
22	1.1388	5.2083	1.1388E-03	53.0915	3.5284E-05	4.7481E-05	1.1409E-03	1.1409E-03
23	1.2485	6.3738	1.2485E-03	64.9724	3.4968E-05	4.7057E-05	1.2451E-03	1.2477E-03
24	1.3389	7.4980	1.3389E-03	76.4322	3.4574E-05	4.6525E-05	1.3358E-03	1.3381E-03
25	1.4336	8.7829	1.4336E-03	89.5296	3.4206E-05	4.6031E-05	1.4304E-03	1.4295E-03
26	1.4925	9.7443	1.4925E-03	99.3301	3.3809E-05	4.5496E-05	1.4962E-03	1.4910E-03
27	1.4111	8.6097	1.4111E-03	87.7641	3.4006E-05	4.5761E-05	1.4181E-03	1.4179E-03
28	1.3237	7.3814	1.3237E-03	75.2434	3.4452E-05	4.6361E-05	1.3267E-03	1.3292E-03
29	1.2279	6.2069	1.2279E-03	63.2711	3.4851E-05	4.6899E-05	1.2308E-03	1.2332E-03
30	1.1276	5.1093	1.1276E-03	52.0824	3.5274E-05	4.7468E-05	1.1314E-03	1.1311E-03
31	1.0771	4.5952	1.0771E-03	46.8417	3.5529E-05	4.7811E-05	1.0807E-03	1.0781E-03



Experiment 02: mPVC Circumferential 50mm

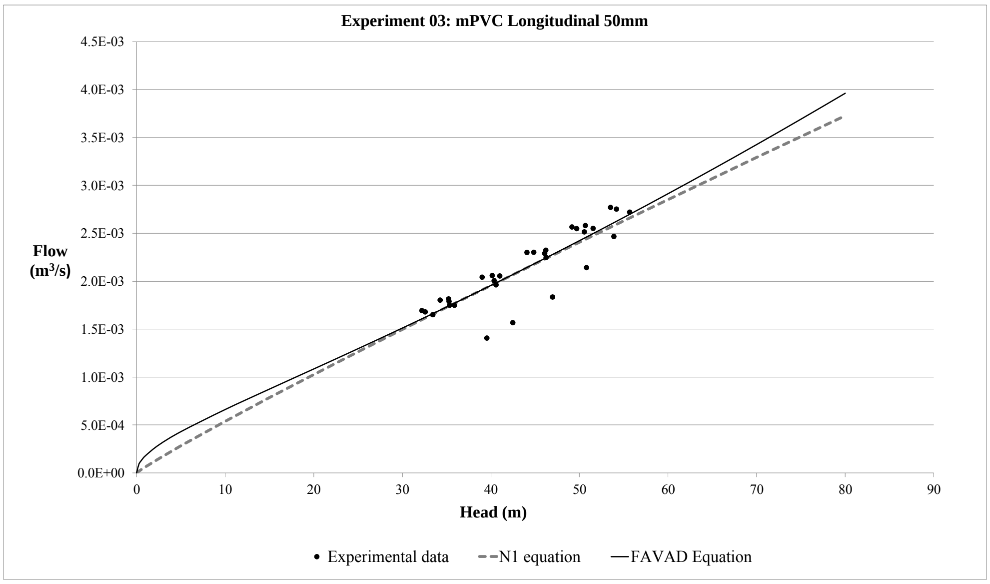




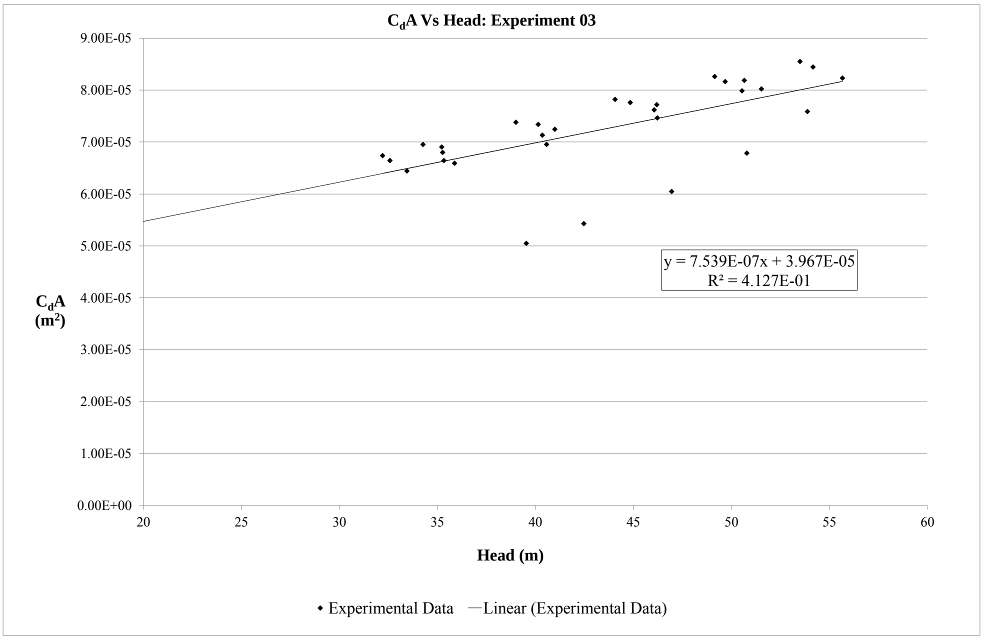
Experiment 03: mPVC Longitudinal 50mm

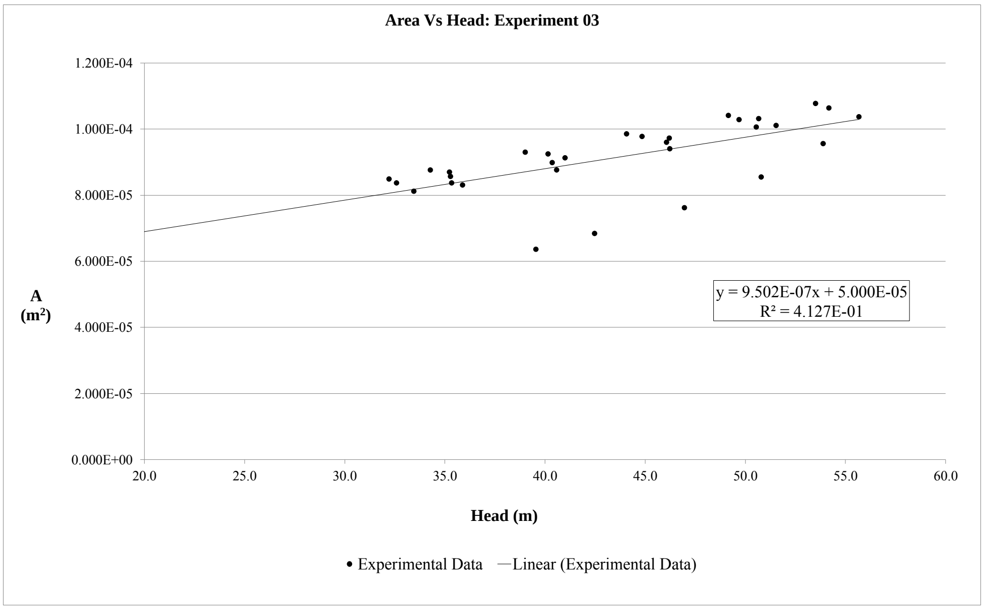
EXPERIMENTAL PARAMETERS		
1 Bar =	10.1937	m
1 l/s =	0.0010	m^3/s
g =	9.81	m/s^2
A_0 =	5.000E-05	m^2
N1 PARAMETERS		
C =	6.326E-05	
N1 =	0.9302	
R^2 =	0.75593	
SSE =	2.868E-04	
FAVAD PARAMETERS		
C_dA_0 =	3.967E-05	m^2
C_d =	0.7934	
m =	9.502E-07	
R^2 =	0.75966	
SSE =	2.883E-04	

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
1	1.4062	3.8793	1.4062E-03	39.5444	5.0483E-05	6.3629E-05	1.9350E-03	1.9354E-03
2	1.5670	4.1669	1.5670E-03	42.4760	5.4280E-05	6.8414E-05	2.0681E-03	2.0697E-03
3	1.8351	4.6069	1.8351E-03	46.9612	6.0458E-05	7.6201E-05	2.2706E-03	2.2788E-03
4	2.1417	4.9829	2.1417E-03	50.7937	6.7843E-05	8.5509E-05	2.4424E-03	2.4612E-03
5	2.4668	5.2862	2.4668E-03	53.8859	7.5865E-05	9.5620E-05	2.5805E-03	2.6108E-03
6	2.7202	5.4614	2.7202E-03	55.6716	8.2306E-05	1.0374E-04	2.6599E-03	2.6982E-03
7	2.5145	4.9586	2.5145E-03	50.5466	7.9846E-05	1.0064E-04	2.4314E-03	2.4494E-03
8	2.2901	4.5193	2.2901E-03	46.0684	7.6174E-05	9.6010E-05	2.2304E-03	2.2368E-03
9	2.0064	3.9593	2.0064E-03	40.3602	7.1302E-05	8.9869E-05	1.9721E-03	1.9726E-03
10	1.7490	3.4664	1.7490E-03	35.3357	6.6424E-05	8.3721E-05	1.7427E-03	1.7460E-03
11	1.6504	3.2814	1.6504E-03	33.4493	6.4425E-05	8.1202E-05	1.6560E-03	1.6623E-03
12	1.7490	3.5200	1.7490E-03	35.8818	6.5916E-05	8.3081E-05	1.7678E-03	1.7703E-03
13	1.9621	3.9807	1.9621E-03	40.5781	6.9537E-05	8.7645E-05	1.9821E-03	1.9825E-03
14	2.2474	4.5352	2.2474E-03	46.2301	7.4621E-05	9.4053E-05	2.2377E-03	2.2444E-03
15	2.5510	5.0559	2.5510E-03	51.5378	8.0223E-05	1.0111E-04	2.4757E-03	2.4970E-03
16	2.7524	5.3145	2.7524E-03	54.1741	8.4424E-05	1.0641E-04	2.5933E-03	2.6249E-03
17	2.5485	4.8745	2.5485E-03	49.6889	8.1622E-05	1.0288E-04	2.3930E-03	2.4083E-03
18	2.3013	4.3993	2.3013E-03	44.8452	7.7583E-05	9.7786E-05	2.1752E-03	2.1796E-03
19	2.0593	3.9386	2.0593E-03	40.1490	7.3374E-05	9.2480E-05	1.9626E-03	1.9629E-03
20	1.8148	3.4559	1.8148E-03	35.2280	6.9031E-05	8.7007E-05	1.7378E-03	1.7412E-03
21	1.6795	3.1966	1.6795E-03	32.5846	6.6422E-05	8.3719E-05	1.6162E-03	1.6242E-03
22	1.7886	3.4607	1.7886E-03	35.2772	6.7985E-05	8.5688E-05	1.7400E-03	1.7434E-03
23	2.0545	4.0221	2.0545E-03	40.9997	7.2439E-05	9.1302E-05	2.0012E-03	2.0018E-03
24	2.3236	4.5324	2.3236E-03	46.2020	7.7176E-05	9.7273E-05	2.2364E-03	2.2431E-03
25	2.5807	4.9703	2.5807E-03	50.6661	8.1852E-05	1.0317E-04	2.4367E-03	2.4551E-03
26	2.7700	5.2490	2.7700E-03	53.5063	8.5493E-05	1.0776E-04	2.5636E-03	2.5923E-03
27	2.5656	4.8221	2.5656E-03	49.1554	8.2613E-05	1.0413E-04	2.3691E-03	2.3828E-03
28	2.2995	4.3234	2.2995E-03	44.0718	7.8198E-05	9.8561E-05	2.1403E-03	2.1436E-03
29	2.0415	3.8269	2.0415E-03	39.0102	7.3793E-05	9.3009E-05	1.9107E-03	1.9111E-03
30	1.8026	3.3621	1.8026E-03	34.2719	6.9514E-05	8.7615E-05	1.6939E-03	1.6987E-03
31	1.6934	3.1600	1.6934E-03	32.2120	6.7360E-05	8.4900E-05	1.5990E-03	1.6078E-03



Experiment 03: mPVC Longitudinal 50mm

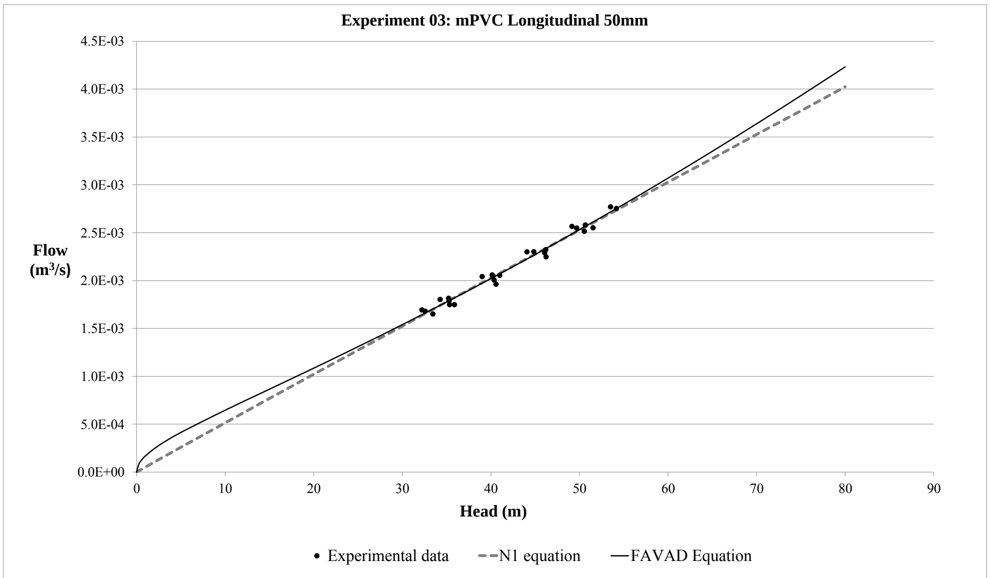




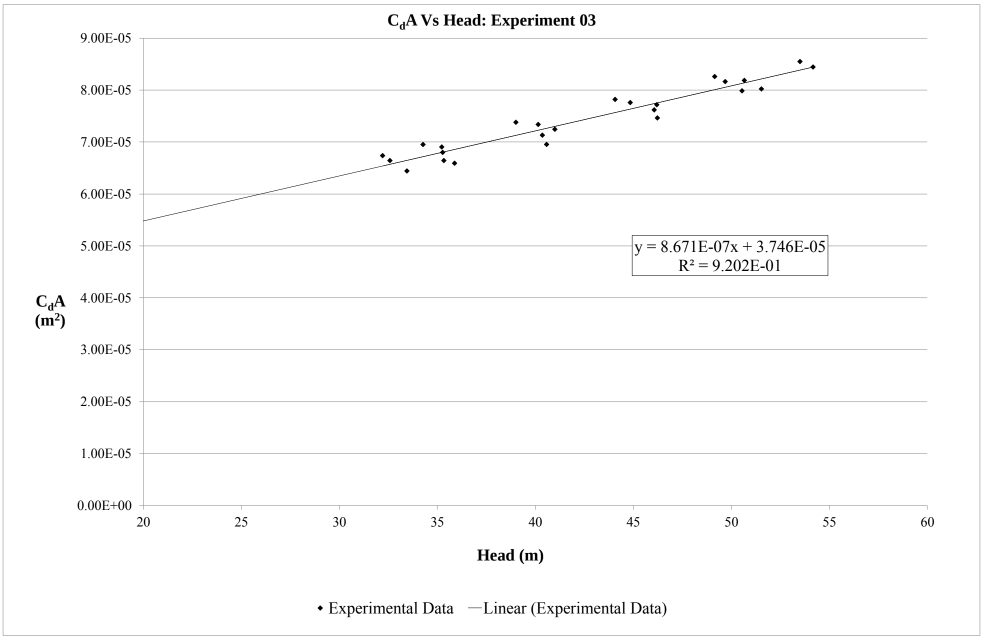
Experiment 03 (Omitted): mPVC Longitudinal 50mm

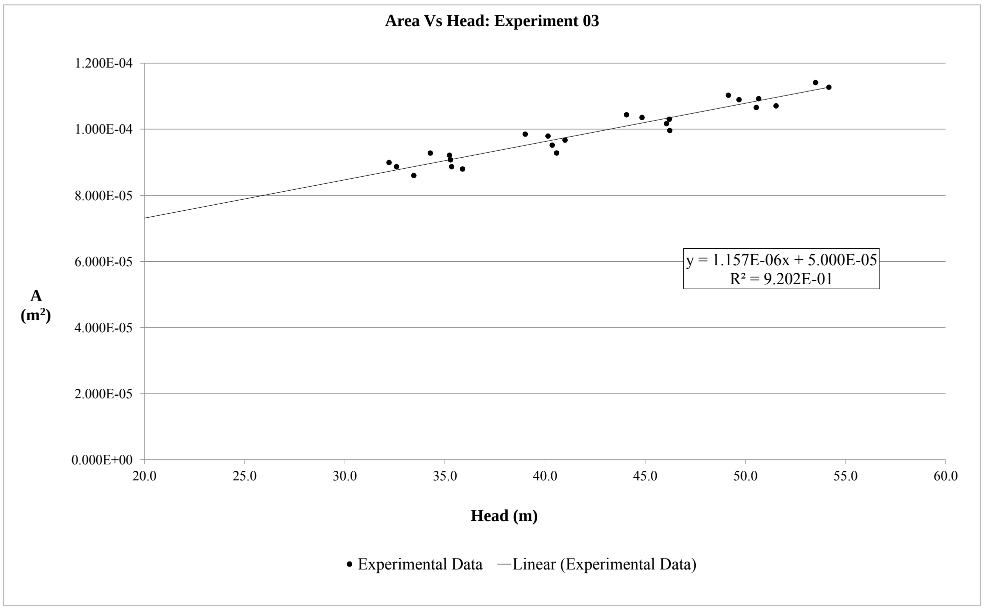
EXPERIMENTAL PARAMETERS	
1 Bar =	10.1937 m
1 l/s =	0.0010 m^3/s
g =	9.81 m/s^2
A_0 =	5.000E-05 m^2
N1 PARAMETERS	
C =	5.284E-05
N1 =	0.9887
R^2 =	0.97857
SSE =	2.375E-04
FAVAD PARAMETERS	
C_dA_0 =	3.746E-05 m^2
C_d =	0.7492
m =	1.157E-06
R^2 =	0.97949
SSE =	2.377E-04

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
7	2.5145	4.9586	2.5145E-03	50.5466	7.9846E-05	1.0658E-04	2.5548E-03	2.5599E-03
8	2.2901	4.5193	2.2901E-03	46.0684	7.6174E-05	1.0168E-04	2.3309E-03	2.3271E-03
9	2.0064	3.9593	2.0064E-03	40.3602	7.1302E-05	9.5176E-05	2.0451E-03	2.0389E-03
10	1.7490	3.4664	1.7490E-03	35.3357	6.6424E-05	8.8664E-05	1.7932E-03	1.7930E-03
11	1.6504	3.2814	1.6504E-03	33.4493	6.4425E-05	8.5997E-05	1.6986E-03	1.7026E-03
12	1.7490	3.5200	1.7490E-03	35.8818	6.5916E-05	8.7987E-05	1.8206E-03	1.8194E-03
13	1.9621	3.9807	1.9621E-03	40.5781	6.9537E-05	9.2821E-05	2.0561E-03	2.0497E-03
14	2.2474	4.5352	2.2474E-03	46.2301	7.4621E-05	9.9607E-05	2.3390E-03	2.3354E-03
15	2.5510	5.0559	2.5510E-03	51.5378	8.0223E-05	1.0708E-04	2.6043E-03	2.6122E-03
16	2.7524	5.3145	2.7524E-03	54.1741	8.4424E-05	1.1269E-04	2.7360E-03	2.7527E-03
17	2.5485	4.8745	2.5485E-03	49.6889	8.1622E-05	1.0895E-04	2.5119E-03	2.5148E-03
18	2.3013	4.3993	2.3013E-03	44.8452	7.7583E-05	1.0356E-04	2.2697E-03	2.2645E-03
19	2.0593	3.9386	2.0593E-03	40.1490	7.3374E-05	9.7942E-05	2.0346E-03	2.0284E-03
20	1.8148	3.4559	1.8148E-03	35.2280	6.9031E-05	9.2145E-05	1.7878E-03	1.7878E-03
21	1.6795	3.1966	1.6795E-03	32.5846	6.6422E-05	8.8662E-05	1.6551E-03	1.6615E-03
22	1.7886	3.4607	1.7886E-03	35.2772	6.7985E-05	9.0748E-05	1.7903E-03	1.7902E-03
23	2.0545	4.0221	2.0545E-03	40.9997	7.2439E-05	9.6694E-05	2.0772E-03	2.0707E-03
24	2.3236	4.5324	2.3236E-03	46.2020	7.7176E-05	1.0302E-04	2.3376E-03	2.3340E-03
25	2.5807	4.9703	2.5807E-03	50.6661	8.1852E-05	1.0926E-04	2.5607E-03	2.5662E-03
26	2.7700	5.2490	2.7700E-03	53.5063	8.5493E-05	1.1412E-04	2.7026E-03	2.7169E-03
27	2.5656	4.8221	2.5656E-03	49.1554	8.2613E-05	1.1027E-04	2.4852E-03	2.4869E-03
28	2.2995	4.3234	2.2995E-03	44.0718	7.8198E-05	1.0438E-04	2.2310E-03	2.2252E-03
29	2.0415	3.8269	2.0415E-03	39.0102	7.3793E-05	9.8502E-05	1.9775E-03	1.9721E-03
30	1.8026	3.3621	1.8026E-03	34.2719	6.9514E-05	9.2789E-05	1.7399E-03	1.7419E-03
31	1.6934	3.1600	1.6934E-03	32.2120	6.7360E-05	8.9914E-05	1.6364E-03	1.6439E-03



Experiment 03 (Omitted): mPVC Longitudinal 50mm

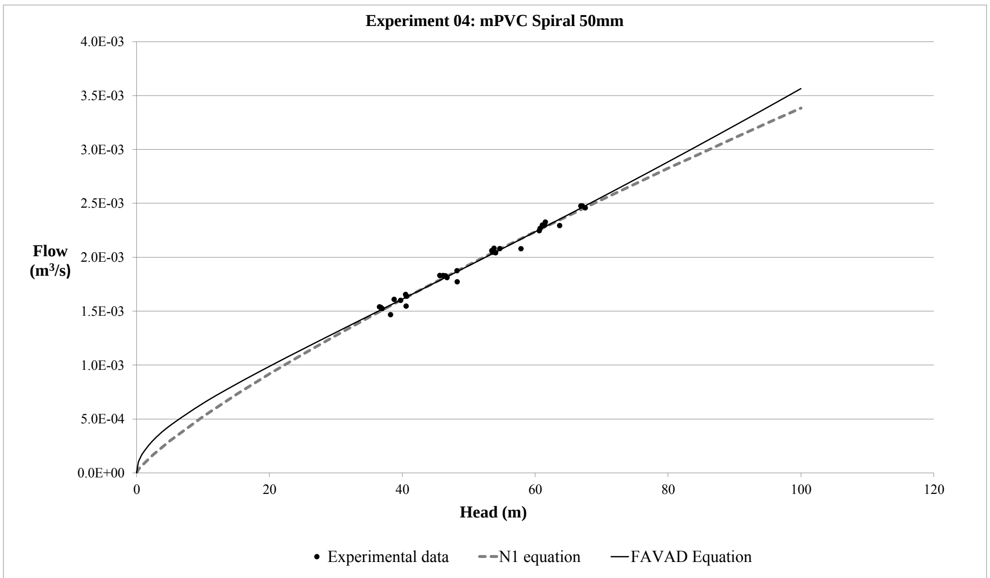




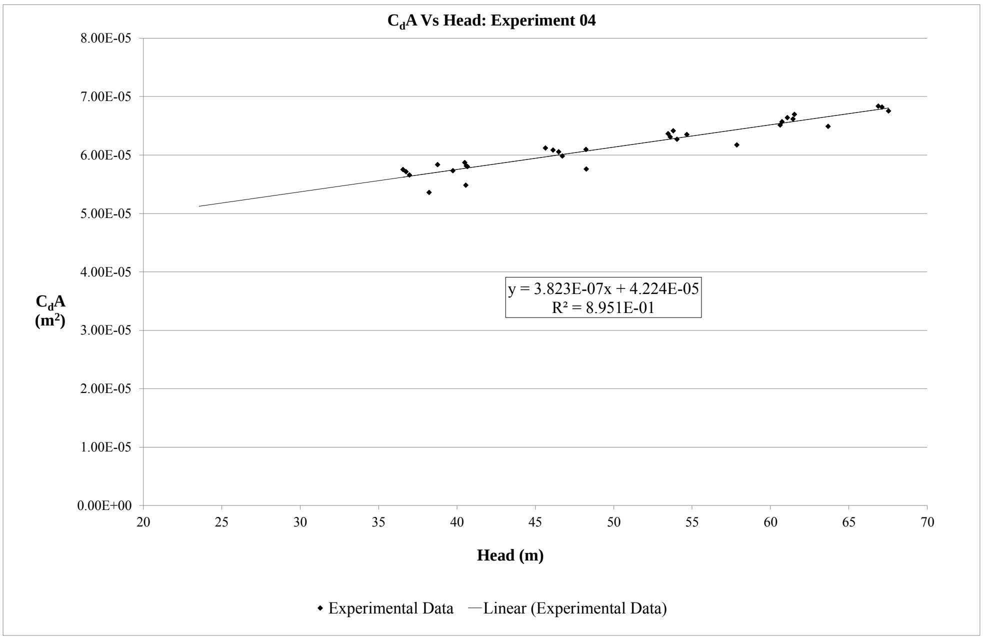
Experiment 04: mPVC Spiral 50mm

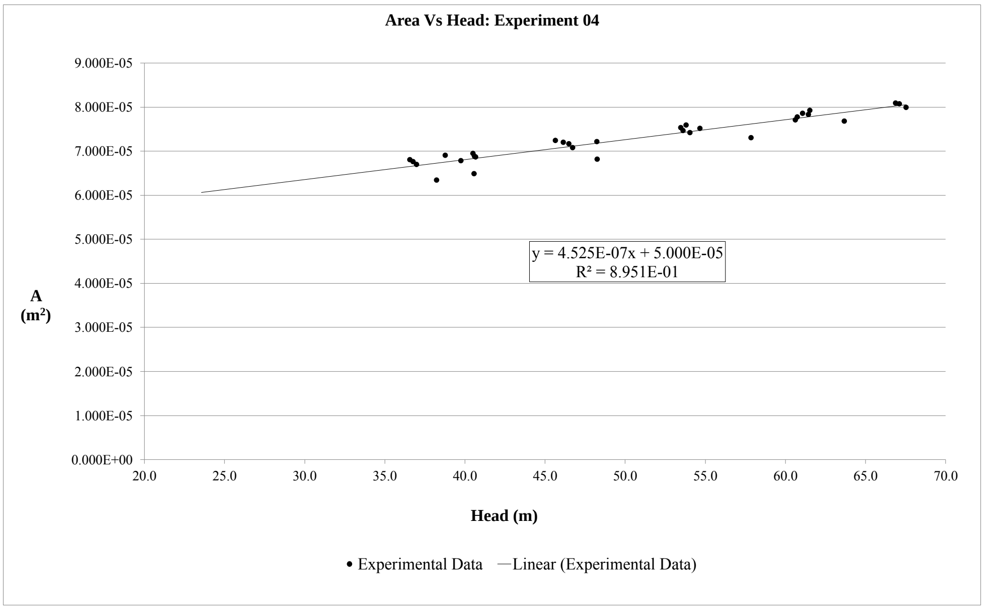
EXPERIMENTAL PARAMETERS	
1 Bar =	10.1937 m
1 l/s =	0.0010 m^3/s
g =	9.81 m/s^2
A_0 =	5.000E-05 m^2
N1 PARAMETERS	
C =	8.096E-05
N1 =	0.8106
R^2 =	0.98372
SSE =	2.402E-04
FAVAD PARAMETERS	
C_dA_0 =	4.224E-05 m^2
C_d =	0.8448
m =	4.525E-07
R^2 =	0.98412
SSE =	2.403E-04

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
1	1.4675	3.7503	1.4675E-03	38.2298	5.3583E-05	6.3429E-05	1.5521E-03	1.5570E-03
2	1.5467	3.9800	1.5467E-03	40.5708	5.4822E-05	6.4896E-05	1.6287E-03	1.6292E-03
3	1.7721	4.7336	1.7721E-03	48.2525	5.7594E-05	6.8178E-05	1.8745E-03	1.8671E-03
4	2.0794	5.6757	2.0794E-03	57.8564	6.1717E-05	7.3059E-05	2.1716E-03	2.1682E-03
5	2.2936	6.2467	2.2936E-03	63.6765	6.4891E-05	7.6816E-05	2.3471E-03	2.3533E-03
6	2.4580	6.6250	2.4580E-03	67.5331	6.7528E-05	7.9937E-05	2.4616E-03	2.4772E-03
7	2.2972	6.0269	2.2972E-03	61.4363	6.6168E-05	7.8327E-05	2.2799E-03	2.2818E-03
8	2.0795	5.3628	2.0795E-03	54.6662	6.3495E-05	7.5163E-05	2.0740E-03	2.0677E-03
9	1.8284	4.5607	1.8284E-03	46.4902	6.0539E-05	7.1663E-05	1.8188E-03	1.8124E-03
10	1.6388	3.9897	1.6388E-03	40.6693	5.8017E-05	6.8678E-05	1.6319E-03	1.6323E-03
11	1.5240	3.6276	1.5240E-03	36.9785	5.6579E-05	6.6977E-05	1.5108E-03	1.5184E-03
12	1.6003	3.8993	1.6003E-03	39.7481	5.7305E-05	6.7836E-05	1.6019E-03	1.6038E-03
13	1.8110	4.5836	1.8110E-03	46.7235	5.9813E-05	7.0805E-05	1.8262E-03	1.8196E-03
14	2.0413	5.3014	2.0413E-03	54.0411	6.2689E-05	7.4209E-05	2.0548E-03	2.0480E-03
15	2.2460	5.9469	2.2460E-03	60.6208	6.5124E-05	7.7091E-05	2.2553E-03	2.2559E-03
16	2.4750	6.5834	2.4750E-03	67.1096	6.8207E-05	8.0740E-05	2.4491E-03	2.4635E-03
17	2.2981	5.9914	2.2981E-03	61.0747	6.6389E-05	7.8589E-05	2.2690E-03	2.2703E-03
18	2.0615	5.2455	2.0615E-03	53.4711	6.3646E-05	7.5341E-05	2.0372E-03	2.0301E-03
19	1.8303	4.5262	1.8303E-03	46.1387	6.0834E-05	7.2013E-05	1.8077E-03	1.8015E-03
20	1.6547	3.9731	1.6547E-03	40.5005	5.8701E-05	6.9489E-05	1.6264E-03	1.6271E-03
21	1.5342	3.6060	1.5342E-03	36.7584	5.7127E-05	6.7625E-05	1.5035E-03	1.5117E-03
22	1.6406	3.9828	1.6406E-03	40.5990	5.8128E-05	6.8810E-05	1.6296E-03	1.6301E-03
23	1.8752	4.7317	1.8752E-03	48.2337	6.0957E-05	7.2159E-05	1.8739E-03	1.8666E-03
24	2.0462	5.2593	2.0462E-03	53.6117	6.3090E-05	7.4683E-05	2.0416E-03	2.0345E-03
25	2.2677	5.9586	2.2677E-03	60.7398	6.5690E-05	7.7761E-05	2.2589E-03	2.2596E-03
26	2.4760	6.5607	2.4760E-03	66.8776	6.8354E-05	8.0915E-05	2.4423E-03	2.4560E-03
27	2.3261	6.0359	2.3261E-03	61.5276	6.6949E-05	7.9251E-05	2.2827E-03	2.2847E-03
28	2.0839	5.2779	2.0839E-03	53.8015	6.4141E-05	7.5927E-05	2.0474E-03	2.0405E-03
29	1.8312	4.4779	1.8312E-03	45.6466	6.1191E-05	7.2436E-05	1.7920E-03	1.7862E-03
30	1.6093	3.8036	1.6093E-03	38.7724	5.8349E-05	6.9071E-05	1.5699E-03	1.5738E-03
31	1.5401	3.5867	1.5401E-03	36.5613	5.7501E-05	6.8068E-05	1.4970E-03	1.5056E-03



Experiment 04: mPVC Spiral 50mm

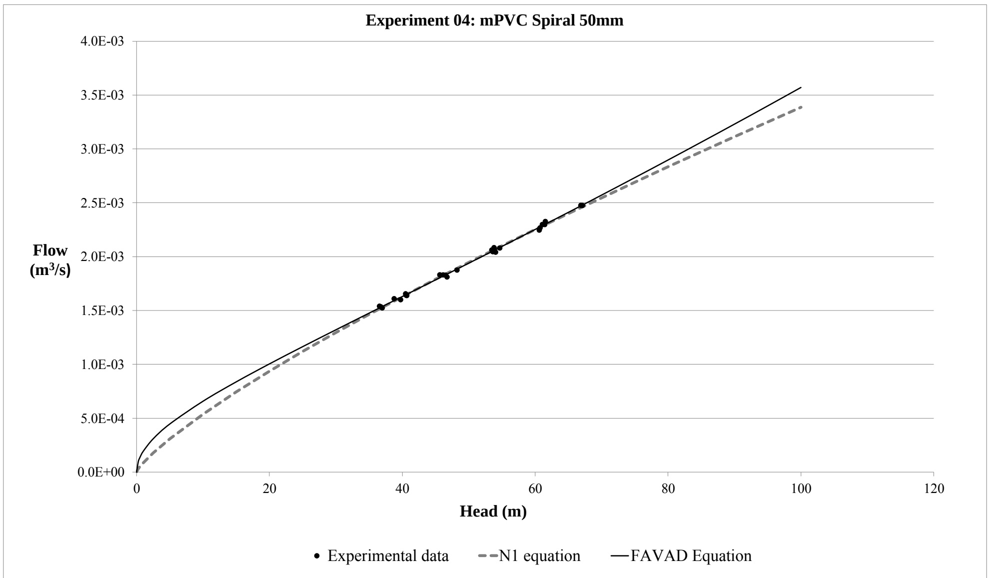




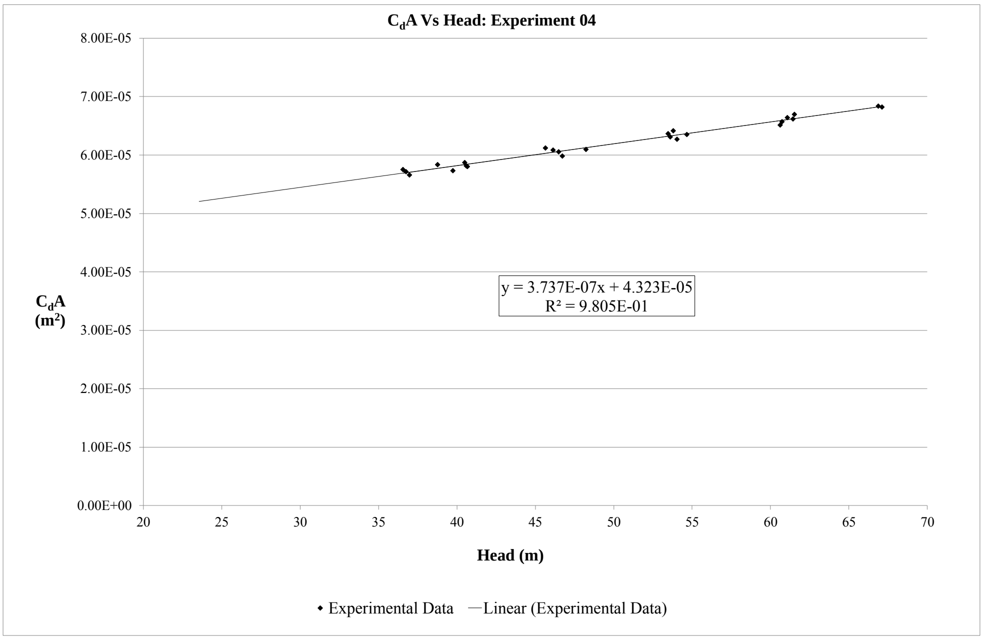
Experiment 04 (Omitted): mPVC Spiral 50mm

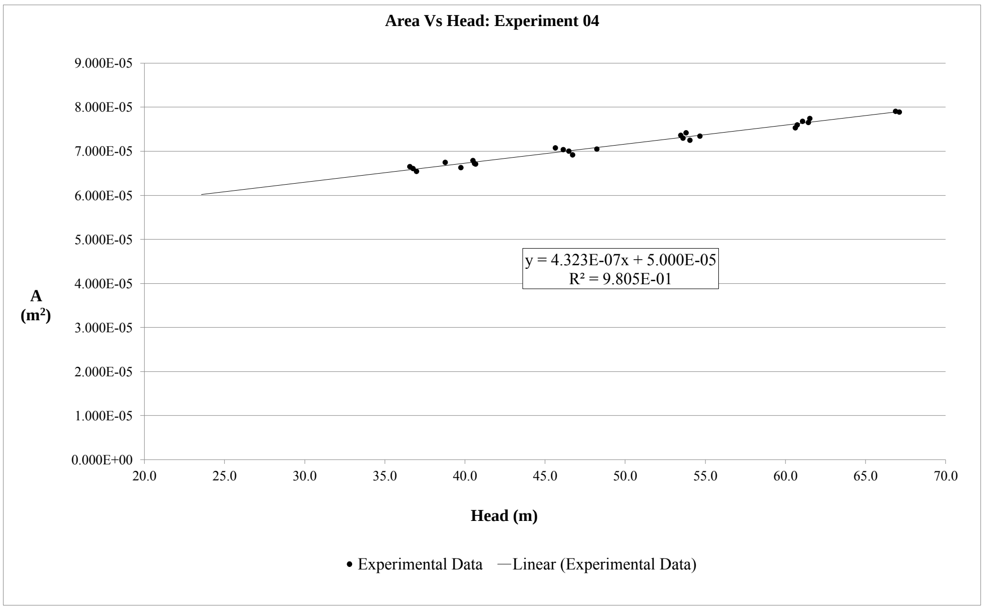
EXPERIMENTAL PARAMETERS		
1 Bar =	10.1937	m
1 l/s =	0.0010	m^3/s
g =	9.81	m/s^2
A_0 =	5.000E-05	m^2
N1 PARAMETERS		
C =	8.570E-05	
N1 =	0.7983	
R^2 =	0.99670	
SSE =	1.936E-04	
FAVAD PARAMETERS		
C_dA_0 =	4.323E-05	m^2
C_d =	0.8646	
m =	4.323E-07	
R^2 =	0.99729	
SSE =	1.937E-04	

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
7	2.2972	6.0269	2.2972E-03	61.4363	6.6168E-05	7.6529E-05	2.2949E-03	2.2981E-03
8	2.0795	5.3628	2.0795E-03	54.6662	6.3495E-05	7.3439E-05	2.0906E-03	2.0849E-03
9	1.8284	4.5607	1.8284E-03	46.4902	6.0539E-05	7.0019E-05	1.8370E-03	1.8304E-03
10	1.6388	3.9897	1.6388E-03	40.6693	5.8017E-05	6.7102E-05	1.6509E-03	1.6505E-03
11	1.5240	3.6276	1.5240E-03	36.9785	5.6579E-05	6.5440E-05	1.5302E-03	1.5367E-03
12	1.6003	3.8993	1.6003E-03	39.7481	5.7305E-05	6.6279E-05	1.6210E-03	1.6221E-03
13	1.8110	4.5836	1.8110E-03	46.7235	5.9813E-05	6.9180E-05	1.8444E-03	1.8376E-03
14	2.0413	5.3014	2.0413E-03	54.0411	6.2689E-05	7.2506E-05	2.0715E-03	2.0653E-03
15	2.2460	5.9469	2.2460E-03	60.6208	6.5124E-05	7.5322E-05	2.2705E-03	2.2723E-03
16	2.4750	6.5834	2.4750E-03	67.1096	6.8207E-05	7.8888E-05	2.4626E-03	2.4788E-03
17	2.2981	5.9914	2.2981E-03	61.0747	6.6389E-05	7.6785E-05	2.2841E-03	2.2866E-03
18	2.0615	5.2455	2.0615E-03	53.4711	6.3646E-05	7.3613E-05	2.0541E-03	2.0475E-03
19	1.8303	4.5262	1.8303E-03	46.1387	6.0834E-05	7.0361E-05	1.8259E-03	1.8195E-03
20	1.6547	3.9731	1.6547E-03	40.5005	5.8701E-05	6.7894E-05	1.6455E-03	1.6453E-03
21	1.5342	3.6060	1.5342E-03	36.7584	5.7127E-05	6.6073E-05	1.5229E-03	1.5299E-03
22	1.6406	3.9828	1.6406E-03	40.5990	5.8128E-05	6.7231E-05	1.6487E-03	1.6483E-03
23	1.8752	4.7317	1.8752E-03	48.2337	6.0957E-05	7.0503E-05	1.8918E-03	1.8844E-03
24	2.0462	5.2593	2.0462E-03	53.6117	6.3090E-05	7.2970E-05	2.0584E-03	2.0519E-03
25	2.2677	5.9586	2.2677E-03	60.7398	6.5690E-05	7.5976E-05	2.2741E-03	2.2760E-03
26	2.4760	6.5607	2.4760E-03	66.8776	6.8354E-05	7.9059E-05	2.4558E-03	2.4714E-03
27	2.3261	6.0359	2.3261E-03	61.5276	6.6949E-05	7.7433E-05	2.2976E-03	2.3010E-03
28	2.0839	5.2779	2.0839E-03	53.8015	6.4141E-05	7.4185E-05	2.0642E-03	2.0578E-03
29	1.8312	4.4779	1.8312E-03	45.6466	6.1191E-05	7.0774E-05	1.8103E-03	1.8043E-03
30	1.6093	3.8036	1.6093E-03	38.7724	5.8349E-05	6.7486E-05	1.5892E-03	1.5920E-03
31	1.5401	3.5867	1.5401E-03	36.5613	5.7501E-05	6.6506E-05	1.5164E-03	1.5238E-03



Experiment 04 (Omitted): mPVC Spiral 50mm

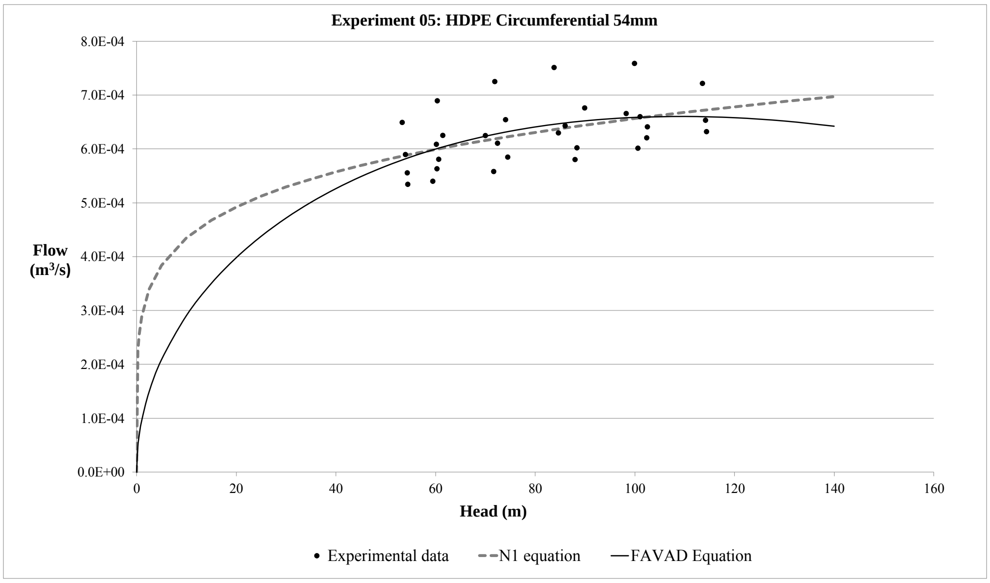




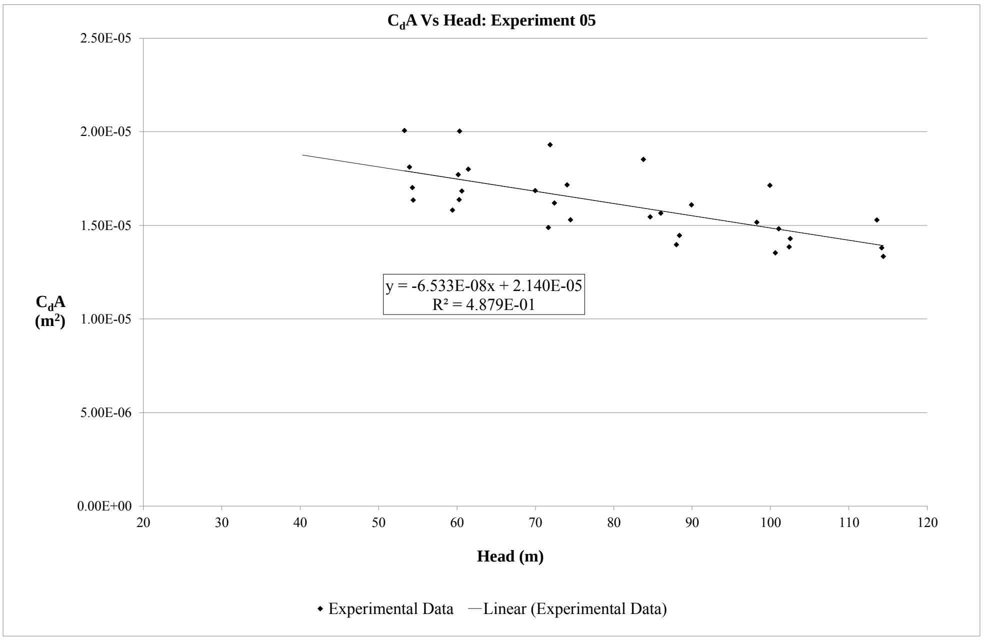
Experiment 05: HDPE Circumeferential 54mm

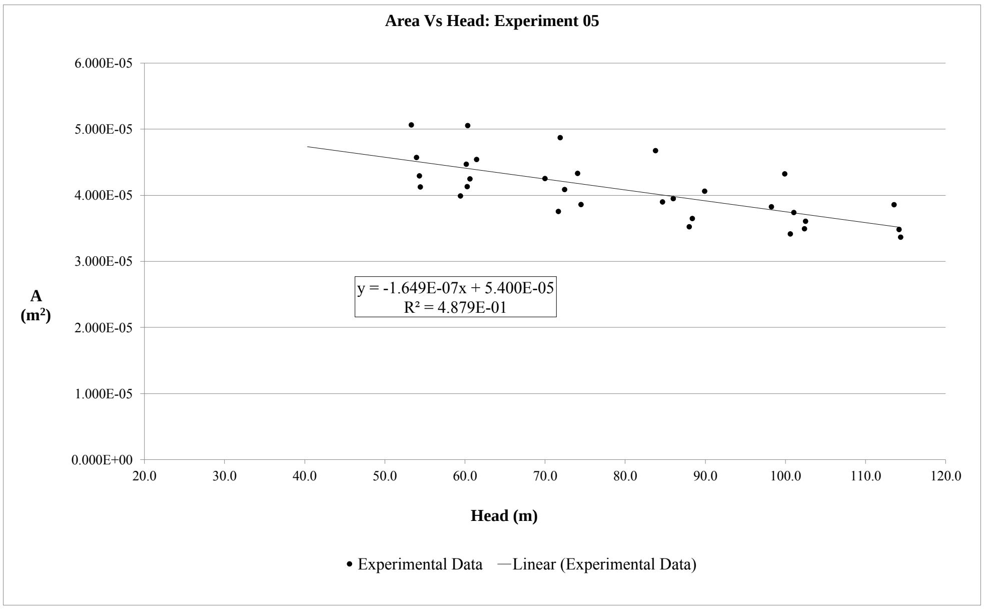
EXPERIMENTAL PARAMETERS	
1 Bar =	10.1937 m
1 l/s =	0.0010 m^3/s
g =	9.81 m/s^2
A_0 =	5.400E-05 m^2
N1 PARAMETERS	
C =	2.880E-04
N1 =	0.1789
R^2 =	0.22504
SSE =	2.465E-05
FAVAD PARAMETERS	
C_dA_0 =	2.140E-05 m^2
C_d =	0.3963
m =	-1.649E-07
R^2 =	0.23290
SSE =	2.472E-05

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
1	0.6490	5.2303	6.4900E-04	53.3165	2.0066E-05	5.0637E-05	5.8649E-04	5.7944E-04
2	0.6892	5.9200	6.8924E-04	60.3466	2.0031E-05	5.0547E-05	5.9963E-04	6.0065E-04
3	0.7250	7.0524	7.2496E-04	71.8900	1.9303E-05	4.8712E-05	6.1870E-04	6.2727E-04
4	0.7510	8.2200	7.5105E-04	83.7920	1.8523E-05	4.6743E-05	6.3588E-04	6.4567E-04
5	0.7586	9.8028	7.5859E-04	99.9262	1.7132E-05	4.3234E-05	6.5623E-04	6.5843E-04
6	0.7215	11.1414	7.2147E-04	113.5722	1.5284E-05	3.8569E-05	6.7143E-04	6.5986E-04
7	0.6656	9.6393	6.6564E-04	98.2600	1.5160E-05	3.8257E-05	6.5426E-04	6.5770E-04
8	0.6429	8.4372	6.4288E-04	86.0065	1.5650E-05	3.9493E-05	6.3886E-04	6.4821E-04
9	0.6246	6.8664	6.2460E-04	69.9939	1.6855E-05	4.2533E-05	6.1575E-04	6.2353E-04
10	0.6085	5.9028	6.0848E-04	60.1708	1.7709E-05	4.4690E-05	5.9932E-04	6.0017E-04
11	0.5894	5.2931	5.8937E-04	53.9562	1.8114E-05	4.5711E-05	5.8774E-04	5.8155E-04
12	0.6249	6.0290	6.2493E-04	61.4573	1.7997E-05	4.5415E-05	6.0159E-04	6.0364E-04
13	0.6542	7.2655	6.5418E-04	74.0624	1.7161E-05	4.3306E-05	6.2200E-04	6.3126E-04
14	0.6759	8.8221	6.7594E-04	89.9293	1.6092E-05	4.0608E-05	6.4398E-04	6.5206E-04
15	0.6597	9.9131	6.5966E-04	101.0510	1.4815E-05	3.7386E-05	6.5755E-04	6.5885E-04
16	0.6530	11.2021	6.5301E-04	114.1903	1.3796E-05	3.4815E-05	6.7208E-04	6.5974E-04
17	0.6204	10.0443	6.2045E-04	102.3882	1.3843E-05	3.4933E-05	6.5909E-04	6.5928E-04
18	0.6020	8.6710	6.0200E-04	88.3898	1.4456E-05	3.6480E-05	6.4199E-04	6.5064E-04
19	0.5847	7.3077	5.8472E-04	74.4923	1.5295E-05	3.8597E-05	6.2265E-04	6.3202E-04
20	0.5630	5.9143	5.6296E-04	60.2883	1.6368E-05	4.1306E-05	5.9953E-04	6.0050E-04
21	0.5555	5.3293	5.5548E-04	54.3255	1.7014E-05	4.2936E-05	5.8846E-04	5.8275E-04
22	0.5806	5.9483	5.8057E-04	60.6348	1.6832E-05	4.2476E-05	6.0014E-04	6.0144E-04
23	0.6105	7.1069	6.1048E-04	72.4454	1.6193E-05	4.0862E-05	6.1955E-04	6.2832E-04
24	0.6296	8.3055	6.2959E-04	84.6638	1.5447E-05	3.8982E-05	6.3706E-04	6.4670E-04
25	0.6409	10.0572	6.4088E-04	102.5203	1.4290E-05	3.6060E-05	6.5925E-04	6.5932E-04
26	0.6319	11.2214	6.3191E-04	114.3871	1.3339E-05	3.3661E-05	6.7229E-04	6.5970E-04
27	0.6012	9.8710	6.0117E-04	100.6222	1.3530E-05	3.4143E-05	6.5705E-04	6.5870E-04
28	0.5802	8.6331	5.8024E-04	88.0031	1.3964E-05	3.5238E-05	6.4149E-04	6.5027E-04
29	0.5580	7.0303	5.5797E-04	71.6651	1.4880E-05	3.7550E-05	6.1835E-04	6.2684E-04
30	0.5399	5.8314	5.3986E-04	59.4437	1.5808E-05	3.9892E-05	5.9801E-04	5.9816E-04
31	0.5342	5.3400	5.3421E-04	54.4343	1.6347E-05	4.1251E-05	5.8867E-04	5.8310E-04



Experiment 05: HDPE Circumeferential 54mm

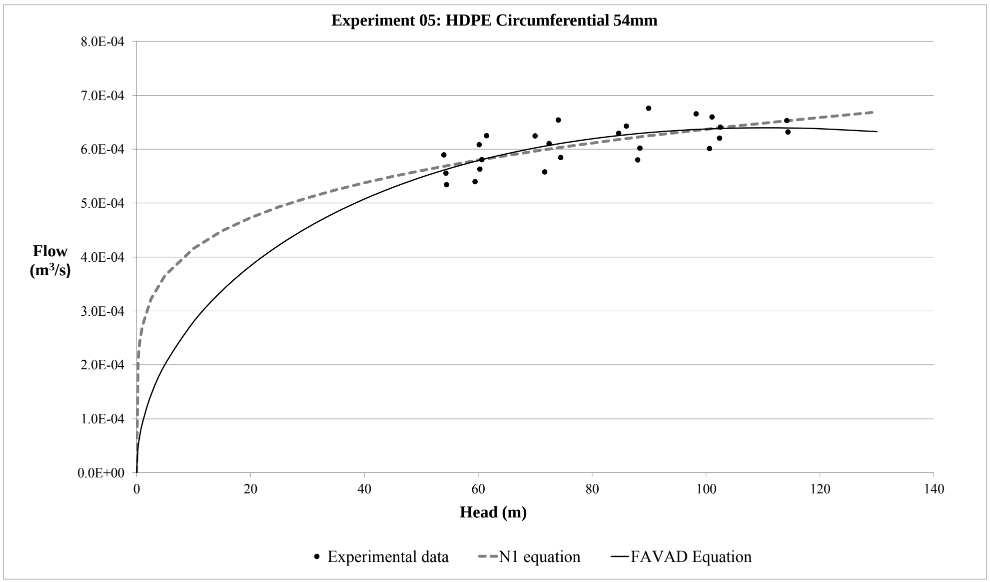




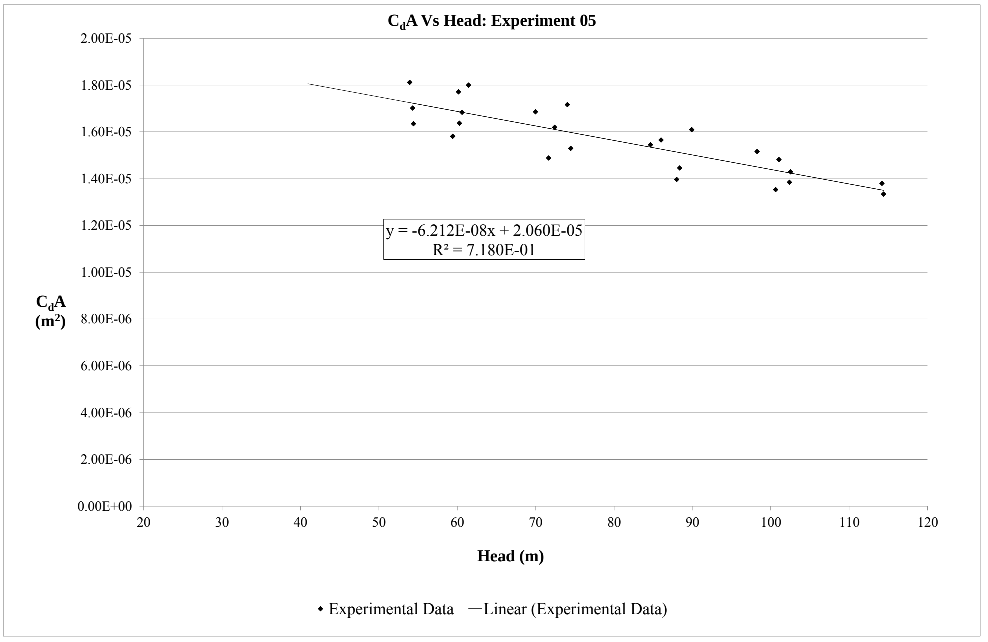
Experiment 05 (Omitted): HDPE Circumeferential 54mm

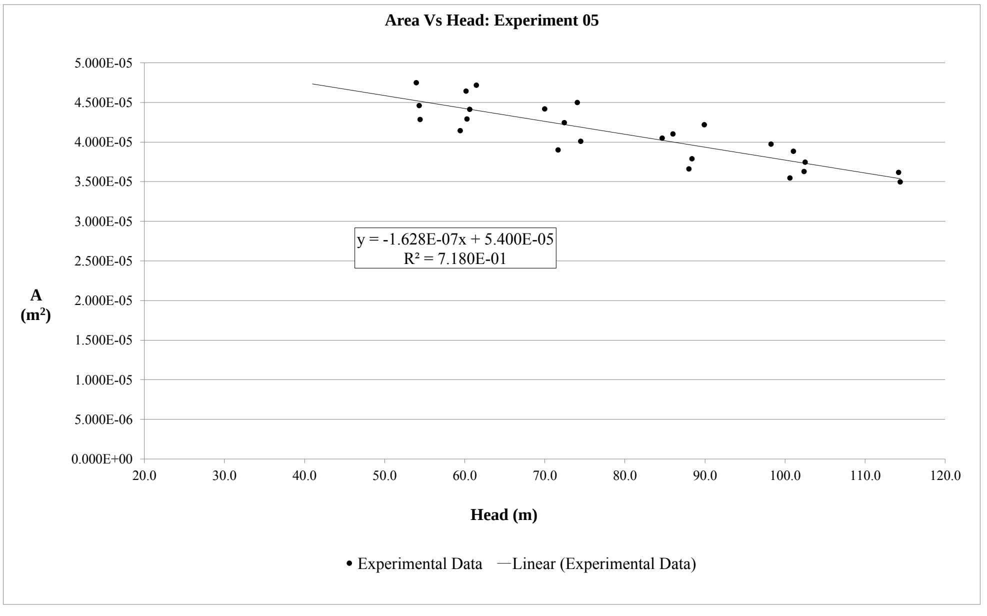
EXPERIMENTAL PARAMETERS	
1 Bar =	10.1937 m
1 l/s =	0.0010 m^3/s
g =	9.81 m/s^2
A_0 =	5.400E-05 m^2
N1 PARAMETERS	
C =	2.718E-04
N1 =	0.1850
R^2 =	0.45868
SSE =	1.860E-05
FAVAD PARAMETERS	
C_dA_0 =	2.060E-05 m^2
C_d =	0.3815
m =	-1.628E-07
R^2 =	0.48198
SSE =	1.862E-05

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
7	0.6656	9.6393	6.6564E-04	98.2600	1.5160E-05	3.9736E-05	6.3502E-04	6.3659E-04
8	0.6429	8.4372	6.4288E-04	86.0065	1.5650E-05	4.1020E-05	6.1956E-04	6.2684E-04
9	0.6246	6.8664	6.2460E-04	69.9939	1.6855E-05	4.4178E-05	5.9640E-04	6.0235E-04
10	0.6085	5.9028	6.0848E-04	60.1708	1.7709E-05	4.6418E-05	5.7995E-04	5.7945E-04
11	0.5894	5.2931	5.8937E-04	53.9562	1.8114E-05	4.7479E-05	5.6837E-04	5.6127E-04
12	0.6249	6.0290	6.2493E-04	61.4573	1.7997E-05	4.7171E-05	5.8222E-04	5.8284E-04
13	0.6542	7.2655	6.5418E-04	74.0624	1.7161E-05	4.4981E-05	6.0266E-04	6.0997E-04
14	0.6759	8.8221	6.7594E-04	89.9293	1.6092E-05	4.2179E-05	6.2470E-04	6.3074E-04
15	0.6597	9.9131	6.5966E-04	101.0510	1.4815E-05	3.8831E-05	6.3832E-04	6.3785E-04
16	0.6530	11.2021	6.5301E-04	114.1903	1.3796E-05	3.6161E-05	6.5292E-04	6.3942E-04
17	0.6204	10.0443	6.2045E-04	102.3882	1.3843E-05	3.6284E-05	6.3987E-04	6.3833E-04
18	0.6020	8.6710	6.0200E-04	88.3898	1.4456E-05	3.7890E-05	6.2270E-04	6.2930E-04
19	0.5847	7.3077	5.8472E-04	74.4923	1.5295E-05	4.0089E-05	6.0331E-04	6.1072E-04
20	0.5630	5.9143	5.6296E-04	60.2883	1.6368E-05	4.2903E-05	5.8015E-04	5.7976E-04
21	0.5555	5.3293	5.5548E-04	54.3255	1.7014E-05	4.4596E-05	5.6908E-04	5.6244E-04
22	0.5806	5.9483	5.8057E-04	60.6348	1.6832E-05	4.4119E-05	5.8077E-04	5.8068E-04
23	0.6105	7.1069	6.1048E-04	72.4454	1.6193E-05	4.2442E-05	6.0021E-04	6.0706E-04
24	0.6296	8.3055	6.2959E-04	84.6638	1.5447E-05	4.0489E-05	6.1776E-04	6.2533E-04
25	0.6409	10.0572	6.4088E-04	102.5203	1.4290E-05	3.7455E-05	6.4002E-04	6.3838E-04
26	0.6319	11.2214	6.3191E-04	114.3871	1.3339E-05	3.4962E-05	6.5312E-04	6.3939E-04
27	0.6012	9.8710	6.0117E-04	100.6222	1.3530E-05	3.5464E-05	6.3782E-04	6.3768E-04
28	0.5802	8.6331	5.8024E-04	88.0031	1.3964E-05	3.6601E-05	6.2220E-04	6.2892E-04
29	0.5580	7.0303	5.5797E-04	71.6651	1.4880E-05	3.9002E-05	5.9901E-04	6.0560E-04
30	0.5399	5.8314	5.3986E-04	59.4437	1.5808E-05	4.1434E-05	5.7864E-04	5.7748E-04
31	0.5342	5.3400	5.3421E-04	54.4343	1.6347E-05	4.2846E-05	5.6930E-04	5.6278E-04



Experiment 05 (Omitted): HDPE Circumeferential 54mm

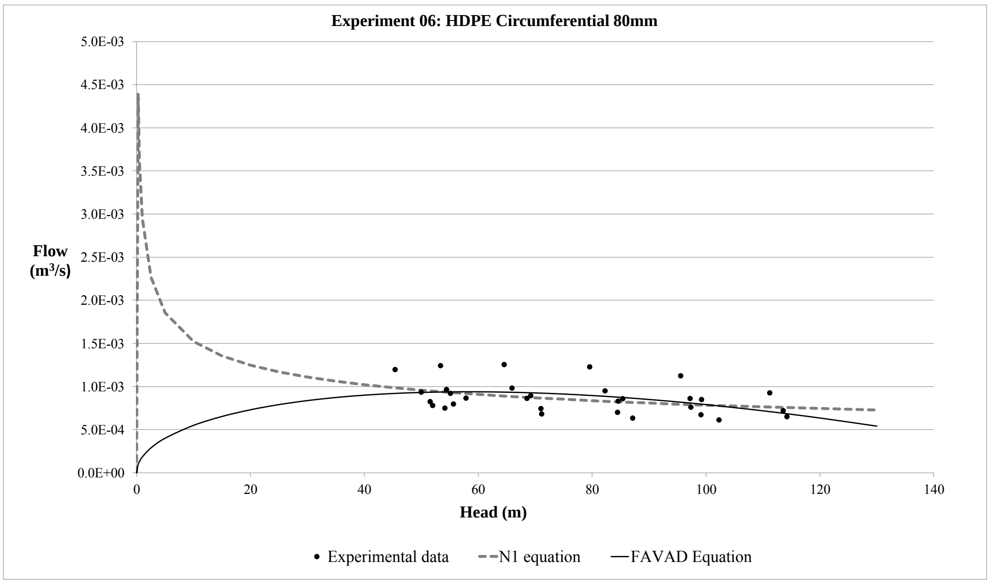




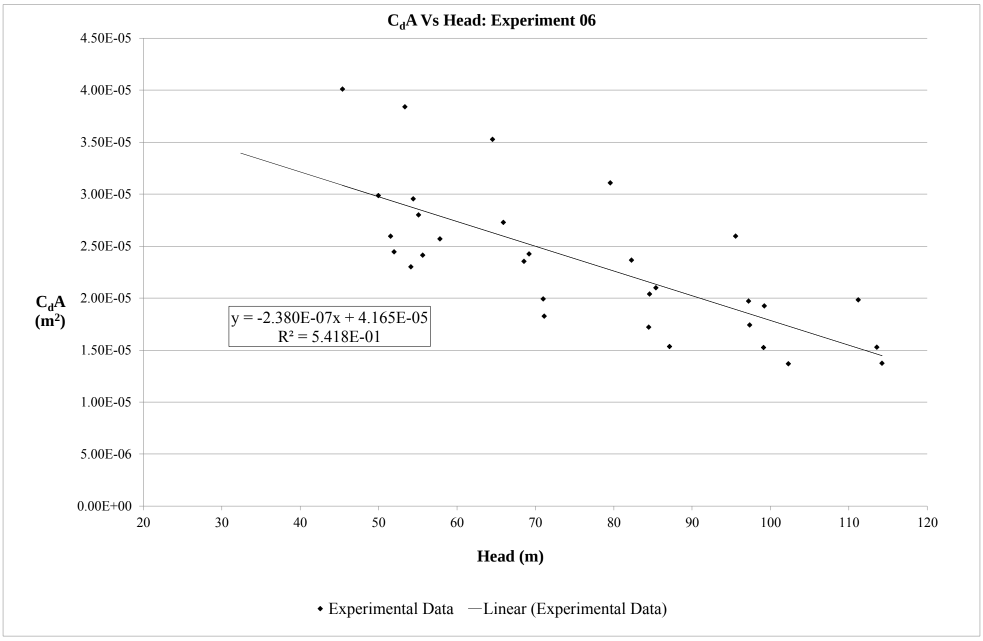
Experiment 06: HDPE Circumeferential 80mm

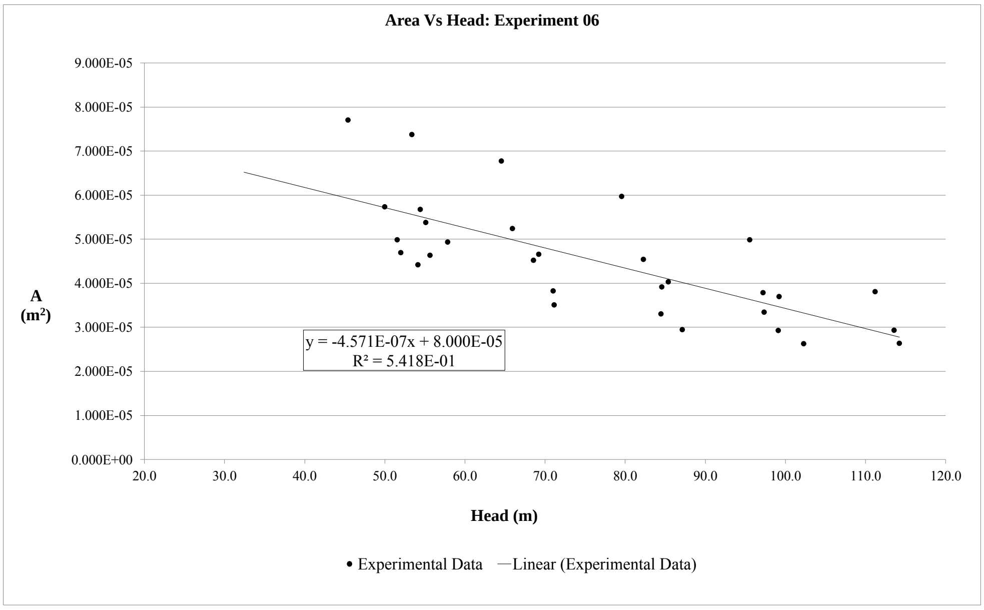
EXPERIMENTAL PARAMETERS	
1 Bar =	10.1937 m
1 l/s =	0.0010 m^3/s
g =	9.81 m/s^2
A_0 =	8.000E-05 m^2
N1 PARAMETERS	
C =	2.952E-03
N1 =	-0.2878
R^2 =	0.14653
SSE =	4.766E-05
FAVAD PARAMETERS	
C_dA_0 =	4.165E-05 m^2
C_d =	0.5206
m =	-4.571E-07
R^2 =	0.12857
SSE =	4.848E-05

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
1	1.1970	4.4547	1.1970E-03	45.4094	4.0103E-05	7.7037E-05	9.8467E-04	9.2055E-04
2	1.2425	5.2359	1.2425E-03	53.3727	3.8398E-05	7.3760E-05	9.3994E-04	9.3668E-04
3	1.2550	6.3324	1.2550E-03	64.5506	3.5265E-05	6.7743E-05	8.8989E-04	9.3545E-04
4	1.2281	7.8050	1.2281E-03	79.5617	3.1083E-05	5.9710E-05	8.3793E-04	8.9742E-04
5	1.1241	9.3736	1.1241E-03	95.5512	2.5961E-05	4.9871E-05	7.9491E-04	8.1873E-04
6	0.9263	10.9086	9.2635E-04	111.1985	1.9832E-05	3.8097E-05	7.6097E-04	7.0932E-04
7	0.8491	9.7329	8.4908E-04	99.2136	1.9245E-05	3.6969E-05	7.8635E-04	7.9583E-04
8	0.8592	8.3764	8.5922E-04	85.3866	2.0992E-05	4.0325E-05	8.2106E-04	8.7296E-04
9	0.8934	6.7897	8.9345E-04	69.2116	2.4245E-05	4.6575E-05	8.7221E-04	9.2777E-04
10	0.9207	5.4064	9.2070E-04	55.1114	2.7999E-05	5.3785E-05	9.3131E-04	9.3821E-04
11	0.9350	4.9034	9.3499E-04	49.9842	2.9857E-05	5.7353E-05	9.5785E-04	9.3171E-04
12	0.9656	5.3393	9.6556E-04	54.4272	2.9548E-05	5.6760E-05	9.3466E-04	9.3769E-04
13	0.9812	6.4676	9.8119E-04	65.9285	2.7281E-05	5.2407E-05	8.8450E-04	9.3359E-04
14	0.9500	8.0714	9.4997E-04	82.2776	2.3644E-05	4.5419E-05	8.2987E-04	8.8664E-04
15	0.8607	9.5359	8.6070E-04	97.2055	1.9709E-05	3.7859E-05	7.9100E-04	8.0860E-04
16	0.7210	11.1407	7.2097E-04	113.5649	1.5274E-05	2.9340E-05	7.5637E-04	6.9025E-04
17	0.6721	9.7233	6.7212E-04	99.1165	1.5241E-05	2.9278E-05	7.8658E-04	7.9646E-04
18	0.7004	8.2864	7.0037E-04	84.4692	1.7204E-05	3.3048E-05	8.2362E-04	8.7714E-04
19	0.7436	6.9662	7.4357E-04	71.0113	1.9921E-05	3.8267E-05	8.6579E-04	9.2377E-04
20	0.7971	5.4586	7.9707E-04	55.6429	2.4124E-05	4.6341E-05	9.2874E-04	9.3855E-04
21	0.8253	5.0567	8.2532E-04	51.5460	2.5952E-05	4.9853E-05	9.4941E-04	9.3434E-04
22	0.8655	5.6743	8.6553E-04	57.8419	2.5693E-05	4.9355E-05	9.1844E-04	9.3929E-04
23	0.8632	6.7255	8.6321E-04	68.5578	2.3536E-05	4.5212E-05	8.7460E-04	9.2908E-04
24	0.8305	8.2964	8.3047E-04	84.5711	2.0388E-05	3.9164E-05	8.2333E-04	8.7668E-04
25	0.7609	9.5497	7.6085E-04	97.3461	1.7410E-05	3.3443E-05	7.9067E-04	8.0772E-04
26	0.6500	11.2048	6.5002E-04	114.2184	1.3731E-05	2.6377E-05	7.5512E-04	6.8487E-04
27	0.6128	10.0338	6.1280E-04	102.2813	1.3680E-05	2.6278E-05	7.7949E-04	7.7534E-04
28	0.6342	8.5471	6.3424E-04	87.1268	1.5340E-05	2.9468E-05	8.1631E-04	8.6469E-04
29	0.6823	6.9786	6.8226E-04	71.1373	1.8262E-05	3.5081E-05	8.6535E-04	9.2347E-04
30	0.7499	5.3104	7.4988E-04	54.1322	2.3010E-05	4.4201E-05	9.3612E-04	9.3744E-04
31	0.7808	5.1007	7.8077E-04	51.9948	2.4445E-05	4.6958E-05	9.4704E-04	9.3499E-04



Experiment 06: HDPE Circumeferential 80mm

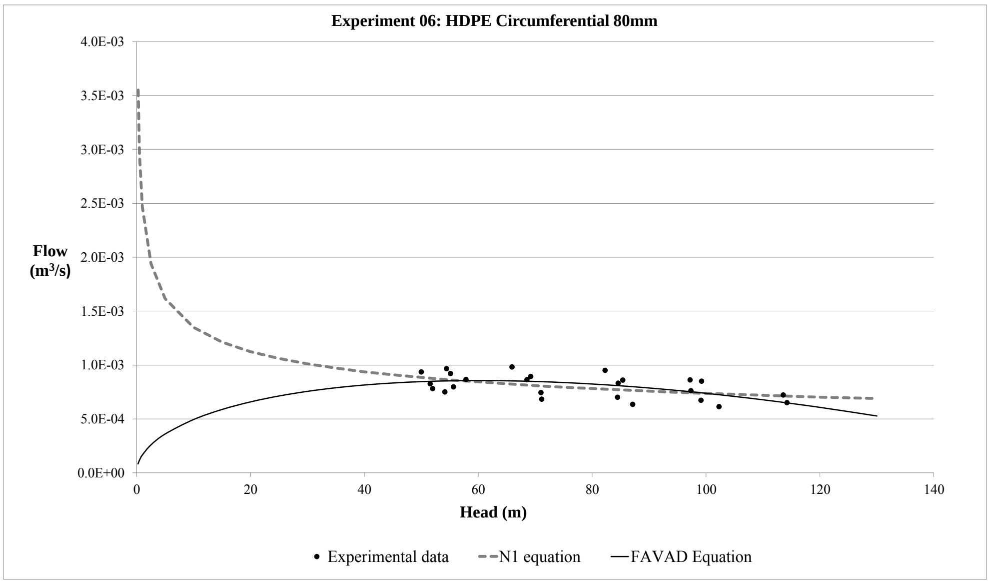




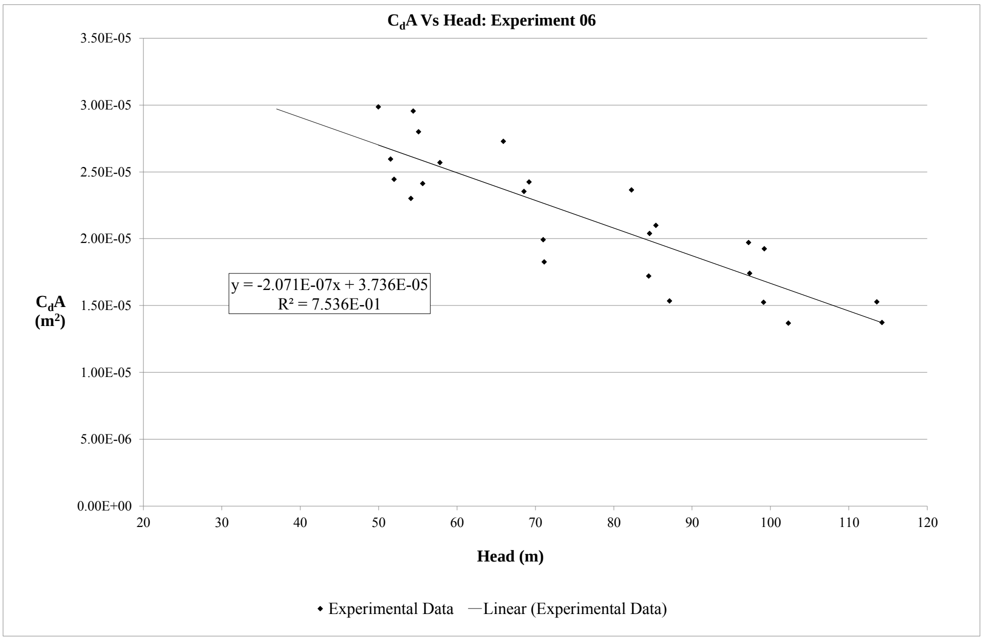
Experiment 06 (Omitted): HDPE Circumeferential 80mm

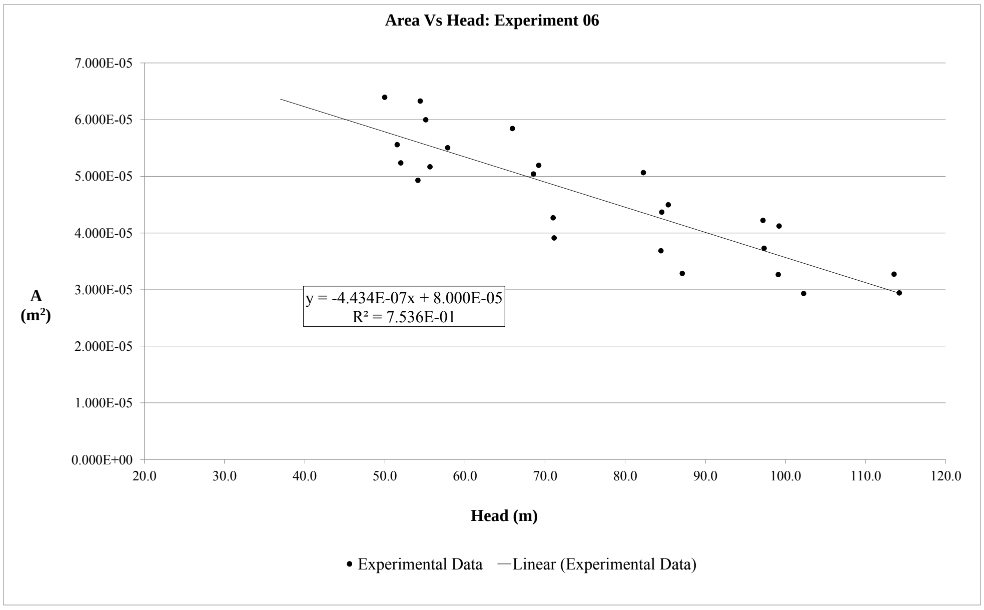
EXPERIMENTAL PARAMETERS		
1 Bar =	10.1937	m
1 l/s =	0.0010	m^3/s
g =	9.81	m/s^2
A_0 =	8.000E-05	m^2
N_{11}PARAMETERS		
C =	2.468E-03	
N1 =	-0.2623	
R^2 =	0.25106	
SSE =	3.248E-05	
FAVAD PARAMETERS		
C_dA_0 =	3.736E-05	m^2
C_d =	0.4670	
m =	-4.434E-07	
R^2 =	0.27516	
SSE =	3.271E-05	

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
7	0.8491	9.7329	8.4908E-04	99.2136	1.9245E-05	4.1211E-05	7.3879E-04	7.4191E-04
8	0.8592	8.3764	8.5922E-04	85.3866	2.0992E-05	4.4953E-05	7.6846E-04	8.0545E-04
9	0.8934	6.7897	8.9345E-04	69.2116	2.4245E-05	5.1919E-05	8.1198E-04	8.4858E-04
10	0.9207	5.4064	9.2070E-04	55.1114	2.7999E-05	5.9958E-05	8.6199E-04	8.5323E-04
11	0.9350	4.9034	9.3499E-04	49.9842	2.9857E-05	6.3935E-05	8.8436E-04	8.4581E-04
12	0.9656	5.3393	9.6556E-04	54.4272	2.9548E-05	6.3273E-05	8.6482E-04	8.5254E-04
13	0.9812	6.4676	9.8119E-04	65.9285	2.7281E-05	5.8420E-05	8.2240E-04	8.5266E-04
14	0.9500	8.0714	9.4997E-04	82.2776	2.3644E-05	5.0631E-05	7.7597E-04	8.1652E-04
15	0.8607	9.5359	8.6070E-04	97.2055	1.9709E-05	4.2204E-05	7.4276E-04	7.5252E-04
16	0.7210	11.1407	7.2097E-04	113.5649	1.5274E-05	3.2707E-05	7.1307E-04	6.5348E-04
17	0.6721	9.7233	6.7212E-04	99.1165	1.5241E-05	3.2638E-05	7.3898E-04	7.4243E-04
18	0.7004	8.2864	7.0037E-04	84.4692	1.7204E-05	3.6841E-05	7.7064E-04	8.0885E-04
19	0.7436	6.9662	7.4357E-04	71.0113	1.9921E-05	4.2659E-05	8.0653E-04	8.4563E-04
20	0.7971	5.4586	7.9707E-04	55.6429	2.4124E-05	5.1659E-05	8.5982E-04	8.5369E-04
21	0.8253	5.0567	8.2532E-04	51.5460	2.5952E-05	5.5574E-05	8.7725E-04	8.4864E-04
22	0.8655	5.6743	8.6553E-04	57.8419	2.5693E-05	5.5019E-05	8.5112E-04	8.5506E-04
23	0.8632	6.7255	8.6321E-04	68.5578	2.3536E-05	5.0400E-05	8.1401E-04	8.4953E-04
24	0.8305	8.2964	8.3047E-04	84.5711	2.0388E-05	4.3658E-05	7.7040E-04	8.0847E-04
25	0.7609	9.5497	7.6085E-04	97.3461	1.7410E-05	3.7281E-05	7.4248E-04	7.5179E-04
26	0.6500	11.2048	6.5002E-04	114.2184	1.3731E-05	2.9404E-05	7.1199E-04	6.4896E-04
27	0.6128	10.0338	6.1280E-04	102.2813	1.3680E-05	2.9293E-05	7.3291E-04	7.2483E-04
28	0.6342	8.5471	6.3424E-04	87.1268	1.5340E-05	3.2849E-05	7.6440E-04	7.9872E-04
29	0.6823	6.9786	6.8226E-04	71.1373	1.8262E-05	3.9106E-05	8.0616E-04	8.4541E-04
30	0.7499	5.3104	7.4988E-04	54.1322	2.3010E-05	4.9274E-05	8.6605E-04	8.5222E-04
31	0.7808	5.1007	7.8077E-04	51.9948	2.4445E-05	5.2347E-05	8.7525E-04	8.4936E-04



Experiment 06 (Omitted): HDPE Circumeferential 80mm

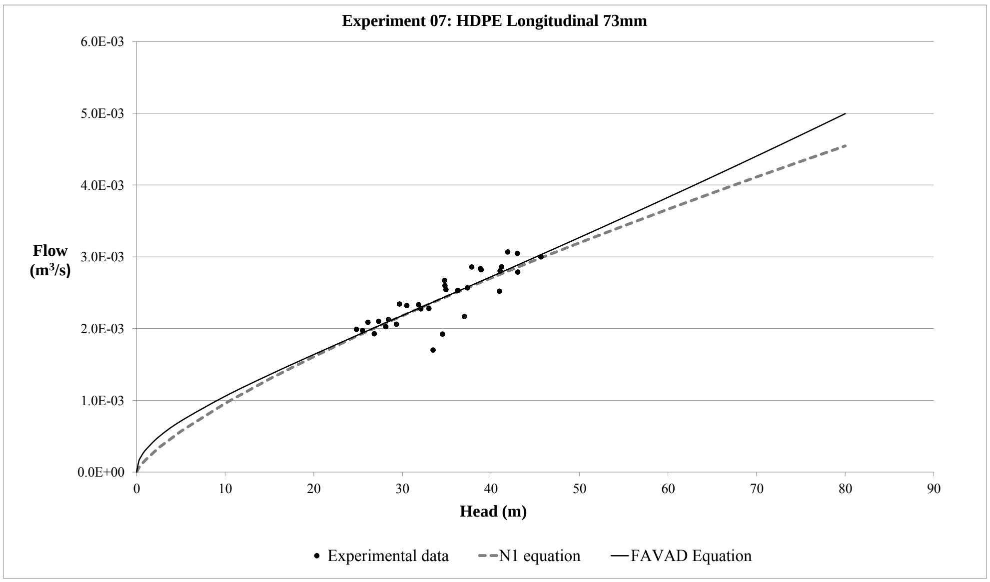




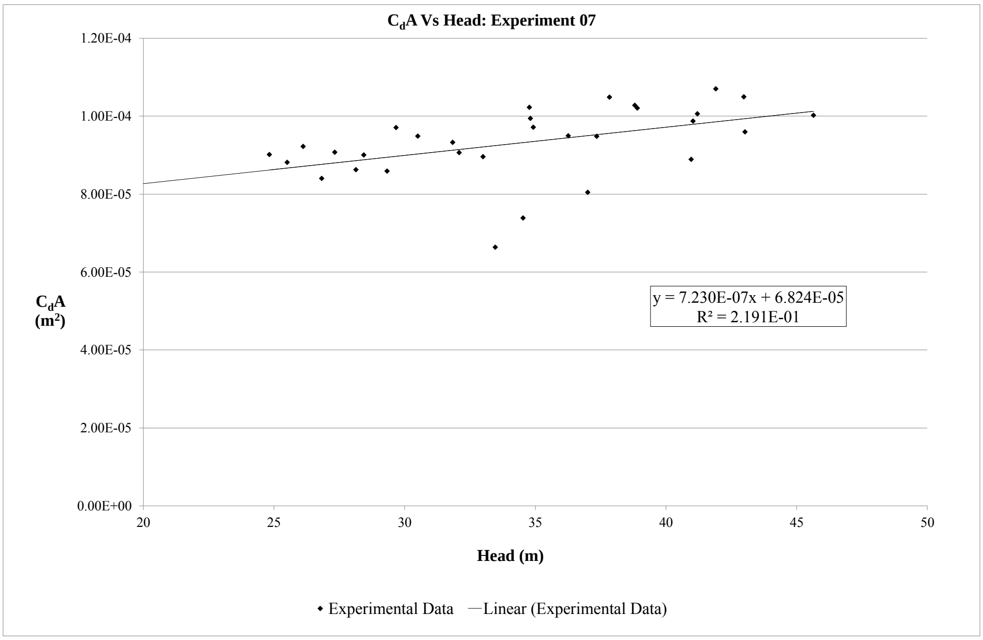
Experiment 07: HDPE Longitudinal 73mm

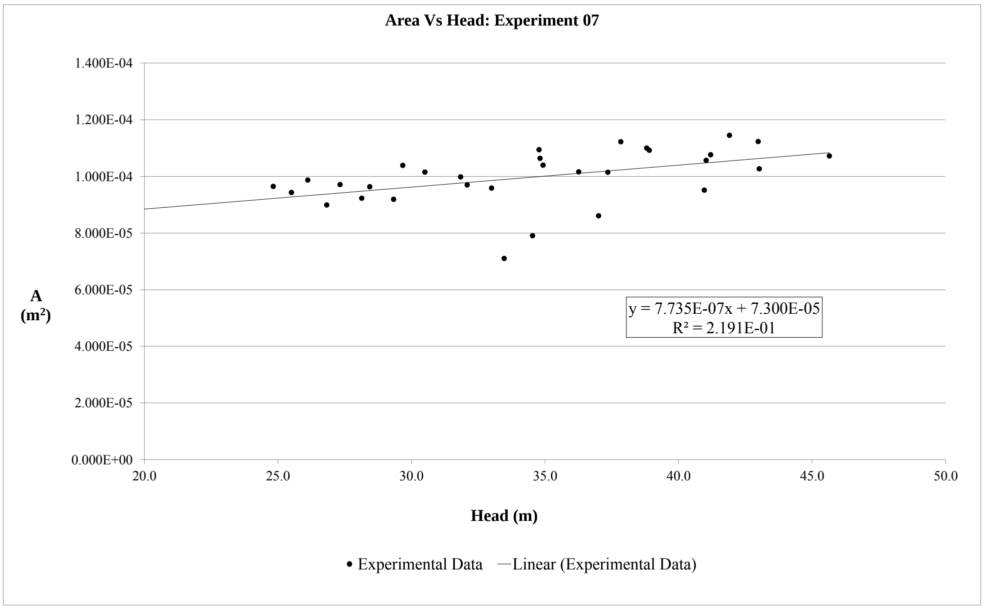
EXPERIMENTAL PARAMETERS	
1 Bar =	10.1937 m
1 l/s =	0.0010 m^3/s
g =	9.81 m/s^2
A_0 =	7.300E-05 m^2
N_1 PARAMETERS	
C =	1.708E-04
N1 =	0.7488
R^2 =	0.69592
SSE =	3.700E-04
FAVAD PARAMETERS	
C_dA_0 =	6.824E-05 m^2
C_d =	0.9347
m =	7.735E-07
R^2 =	0.69961
SSE =	3.717E-04

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
1	1.7009	3.2834	1.7009E-03	33.4704	6.6374E-05	7.1009E-05	2.3665E-03	2.3687E-03
2	1.9226	3.3876	1.9226E-03	34.5320	7.3862E-05	7.9020E-05	2.4225E-03	2.4259E-03
3	2.1674	3.6303	2.1674E-03	37.0066	8.0437E-05	8.6054E-05	2.5513E-03	2.5596E-03
4	2.5205	4.0186	2.5205E-03	40.9645	8.8906E-05	9.5115E-05	2.7530E-03	2.7741E-03
5	2.7877	4.2207	2.7877E-03	43.0244	9.5947E-05	1.0265E-04	2.8560E-03	2.8863E-03
6	2.9990	4.4779	2.9990E-03	45.6466	1.0021E-04	1.0721E-04	2.9854E-03	3.0296E-03
7	2.8017	4.0255	2.8017E-03	41.0348	9.8742E-05	1.0564E-04	2.7566E-03	2.7779E-03
8	2.5327	3.5572	2.5327E-03	36.2614	9.4953E-05	1.0158E-04	2.5128E-03	2.5193E-03
9	2.2739	3.1476	2.2739E-03	32.0855	9.0630E-05	9.6958E-05	2.2928E-03	2.2941E-03
10	2.0265	2.7600	2.0265E-03	28.1346	8.6252E-05	9.2275E-05	2.0780E-03	2.0811E-03
11	1.9274	2.6317	1.9274E-03	26.8270	8.4012E-05	8.9879E-05	2.0052E-03	2.0104E-03
12	2.0605	2.8772	2.0605E-03	29.3297	8.5895E-05	9.1893E-05	2.1437E-03	2.1455E-03
13	2.2794	3.2372	2.2794E-03	32.9994	8.9583E-05	9.5839E-05	2.3415E-03	2.3433E-03
14	2.5667	3.6641	2.5667E-03	37.3510	9.4813E-05	1.0143E-04	2.5691E-03	2.5782E-03
15	2.8600	4.0421	2.8600E-03	41.2036	1.0059E-04	1.0761E-04	2.7650E-03	2.7871E-03
16	3.0476	4.2166	3.0476E-03	42.9822	1.0495E-04	1.1228E-04	2.8539E-03	2.8840E-03
17	2.8361	3.8071	2.8361E-03	38.8088	1.0278E-04	1.0996E-04	2.6438E-03	2.6571E-03
18	2.5982	3.4152	2.5982E-03	34.8132	9.9414E-05	1.0636E-04	2.4372E-03	2.4411E-03
19	2.3207	2.9924	2.3207E-03	30.5037	9.4864E-05	1.0149E-04	2.2076E-03	2.2088E-03
20	2.1012	2.6807	2.1012E-03	27.3261	9.0746E-05	9.7083E-05	2.0331E-03	2.0374E-03
21	1.9718	2.5021	1.9718E-03	25.5053	8.8144E-05	9.4300E-05	1.9308E-03	1.9389E-03
22	2.1269	2.7897	2.1269E-03	28.4369	9.0043E-05	9.6331E-05	2.0947E-03	2.0974E-03
23	2.3313	3.1234	2.3313E-03	31.8394	9.3273E-05	9.9787E-05	2.2796E-03	2.2808E-03
24	2.5430	3.4262	2.5430E-03	34.9257	9.7145E-05	1.0393E-04	2.4431E-03	2.4472E-03
25	2.8201	3.8166	2.8201E-03	38.9047	1.0207E-04	1.0920E-04	2.6487E-03	2.6623E-03
26	3.0679	4.1110	3.0679E-03	41.9066	1.0699E-04	1.1446E-04	2.8003E-03	2.8253E-03
27	2.8574	3.7119	2.8574E-03	37.8377	1.0487E-04	1.1219E-04	2.5941E-03	2.6045E-03
28	2.6712	3.4115	2.6712E-03	34.7761	1.0226E-04	1.0940E-04	2.4353E-03	2.4391E-03
29	2.3421	2.9110	2.3421E-03	29.6742	9.7066E-05	1.0384E-04	2.1625E-03	2.1641E-03
30	2.0877	2.5621	2.0877E-03	26.1169	9.2225E-05	9.8665E-05	1.9653E-03	1.9720E-03
31	1.9893	2.4352	1.9893E-03	24.8234	9.0141E-05	9.6436E-05	1.8920E-03	1.9019E-03



Experiment 07: HDPE Longitudinal 73mm

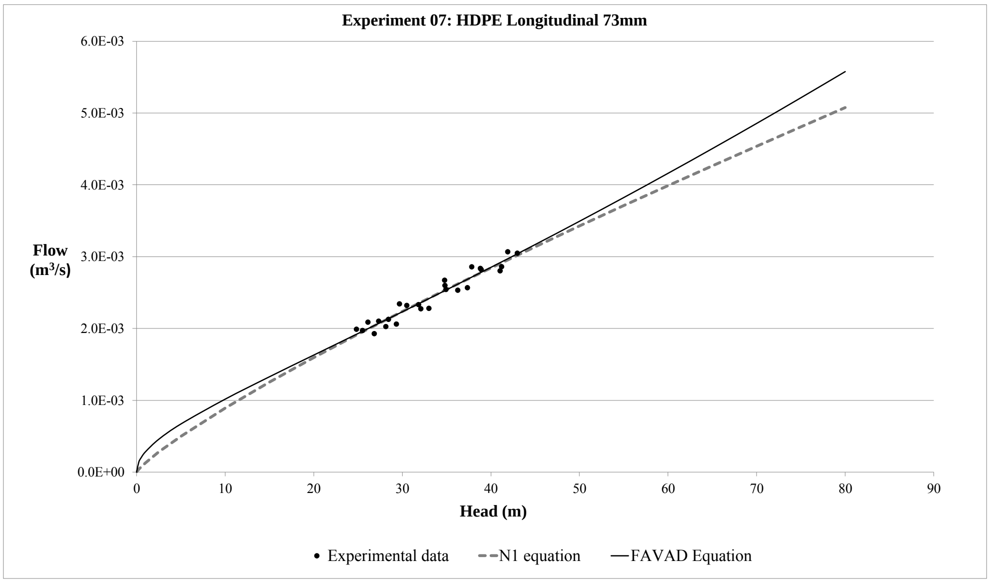




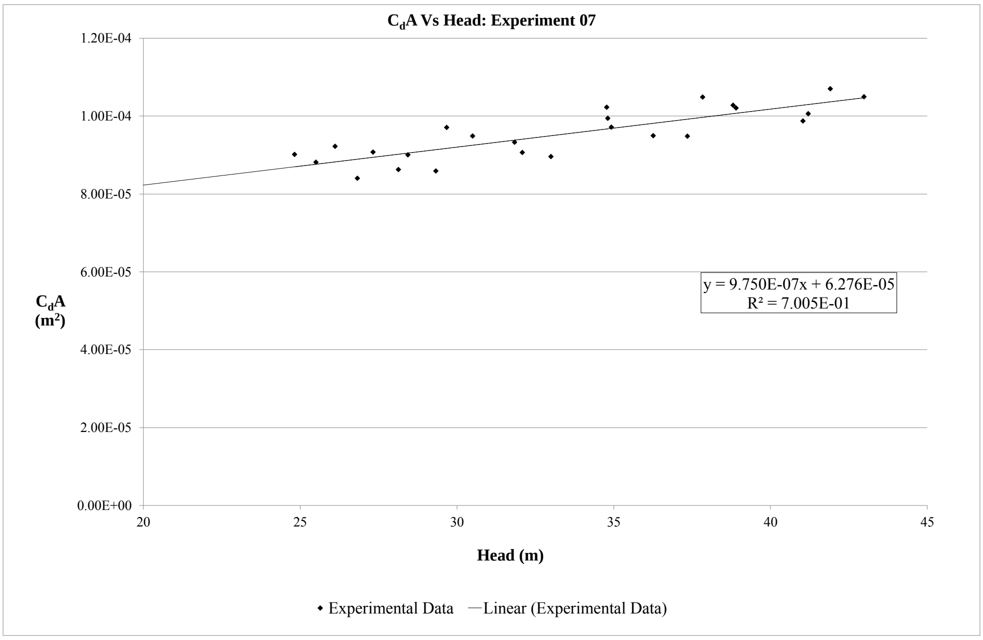
Experiment 07 (Omitted): HDPE Longitudinal 73mm

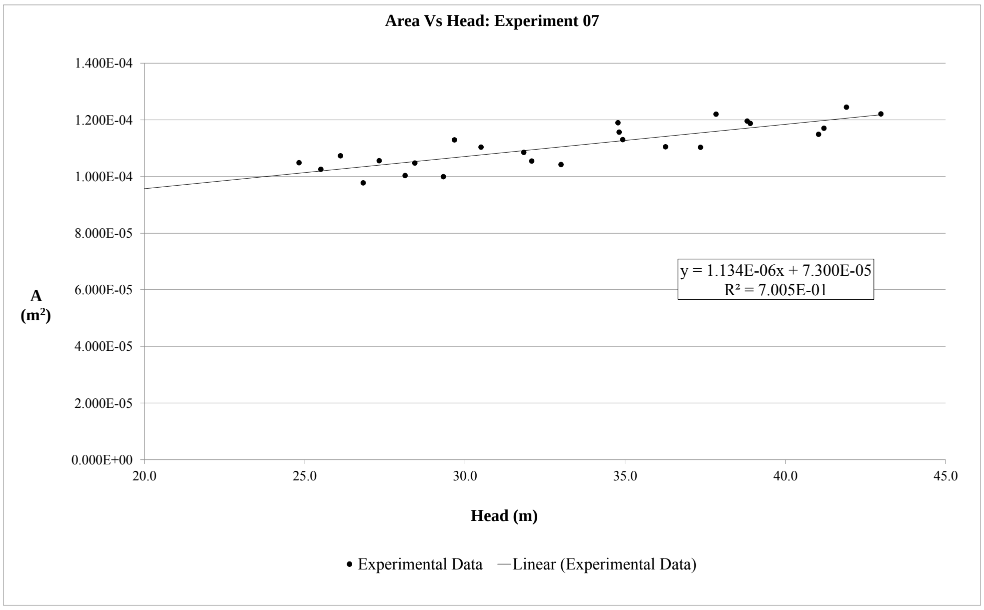
EXPERIMENTAL PARAMETERS		
1 Bar =	10.1937	m
1 l/s =	0.0010	m^3/s
g =	9.81	m/s^2
A_0 =	7.300E-05	m^2
N1 PARAMETERS		
C =	1.304E-04	
N1 =	0.8355	
R^2 =	0.93448	
SSE =	3.038E-04	
FAVAD PARAMETERS		
C_dA_0 =	6.276E-05	m^2
C_d =	0.8597	
m =	1.134E-06	
R^2 =	0.93562	
SSE =	3.040E-04	

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
7	2.8017	4.0255	2.8017E-03	41.0348	9.8742E-05	1.1486E-04	2.9048E-03	2.9159E-03
8	2.5327	3.5572	2.5327E-03	36.2614	9.4953E-05	1.1045E-04	2.6197E-03	2.6169E-03
9	2.2739	3.1476	2.2739E-03	32.0855	9.0630E-05	1.0542E-04	2.3652E-03	2.3595E-03
10	2.0265	2.7600	2.0265E-03	28.1346	8.6252E-05	1.0033E-04	2.1192E-03	2.1189E-03
11	1.9274	2.6317	1.9274E-03	26.8270	8.4012E-05	9.7725E-05	2.0366E-03	2.0399E-03
12	2.0605	2.8772	2.0605E-03	29.3297	8.5895E-05	9.9916E-05	2.1942E-03	2.1914E-03
13	2.2794	3.2372	2.2794E-03	32.9994	8.9583E-05	1.0421E-04	2.4213E-03	2.4155E-03
14	2.5667	3.6641	2.5667E-03	37.3510	9.4813E-05	1.1029E-04	2.6853E-03	2.6847E-03
15	2.8600	4.0421	2.8600E-03	41.2036	1.0059E-04	1.1701E-04	2.9148E-03	2.9266E-03
16	3.0476	4.2166	3.0476E-03	42.9822	1.0495E-04	1.2208E-04	3.0196E-03	3.0394E-03
17	2.8361	3.8071	2.8361E-03	38.8088	1.0278E-04	1.1956E-04	2.7726E-03	2.7758E-03
18	2.5982	3.4152	2.5982E-03	34.8132	9.9414E-05	1.1564E-04	2.5320E-03	2.5272E-03
19	2.3207	2.9924	2.3207E-03	30.5037	9.4864E-05	1.1035E-04	2.2673E-03	2.2628E-03
20	2.1012	2.6807	2.1012E-03	27.3261	9.0746E-05	1.0556E-04	2.0682E-03	2.0700E-03
21	1.9718	2.5021	1.9718E-03	25.5053	8.8144E-05	1.0253E-04	1.9525E-03	1.9601E-03
22	2.1269	2.7897	2.1269E-03	28.4369	9.0043E-05	1.0474E-04	2.1382E-03	2.1372E-03
23	2.3313	3.1234	2.3313E-03	31.8394	9.3273E-05	1.0850E-04	2.3500E-03	2.3444E-03
24	2.5430	3.4262	2.5430E-03	34.9257	9.7145E-05	1.1300E-04	2.5388E-03	2.5342E-03
25	2.8201	3.8166	2.8201E-03	38.9047	1.0207E-04	1.1873E-04	2.7783E-03	2.7818E-03
26	3.0679	4.1110	3.0679E-03	41.9066	1.0699E-04	1.2446E-04	2.9563E-03	2.9711E-03
27	2.8574	3.7119	2.8574E-03	37.8377	1.0487E-04	1.2199E-04	2.7145E-03	2.7151E-03
28	2.6712	3.4115	2.6712E-03	34.7761	1.0226E-04	1.1895E-04	2.5297E-03	2.5249E-03
29	2.3421	2.9110	2.3421E-03	29.6742	9.7066E-05	1.1291E-04	2.2157E-03	2.2124E-03
30	2.0877	2.5621	2.0877E-03	26.1169	9.2225E-05	1.0728E-04	1.9915E-03	1.9970E-03
31	1.9893	2.4352	1.9893E-03	24.8234	9.0141E-05	1.0485E-04	1.9087E-03	1.9191E-03



Experiment 07 (Omitted): HDPE Longitudinal 73mm

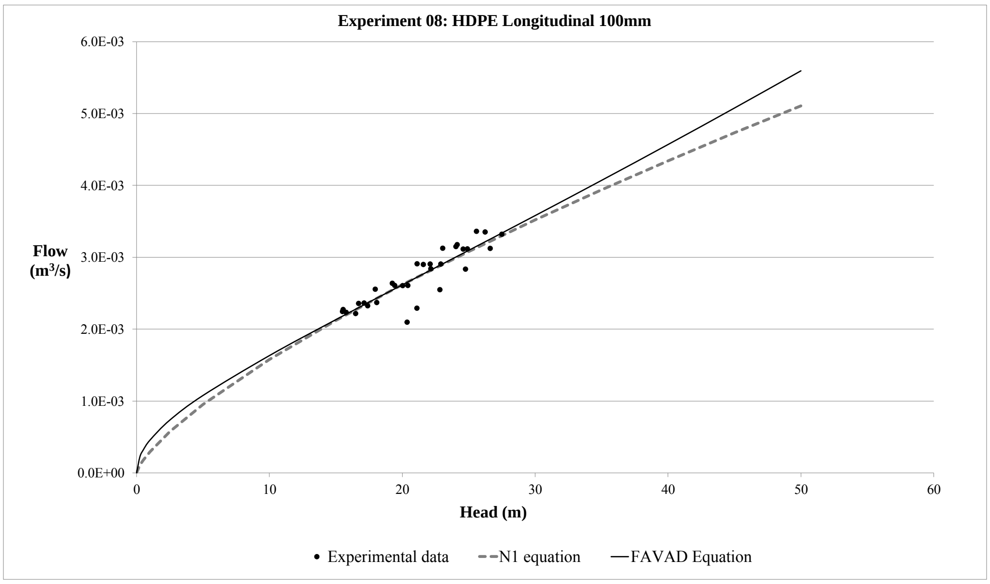




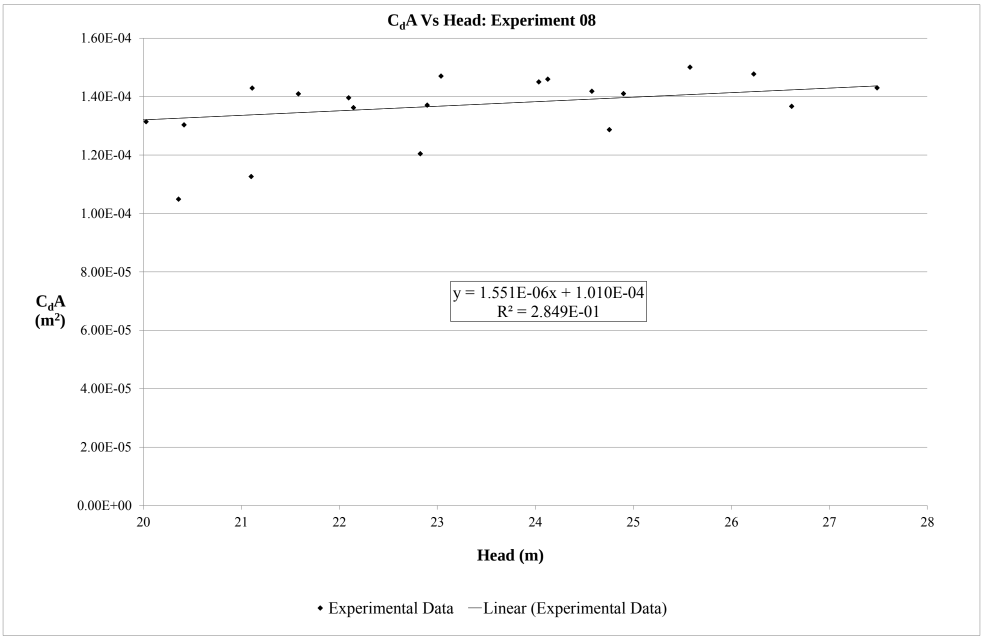
Experiment 08: HDPE Longitudinal 100mm

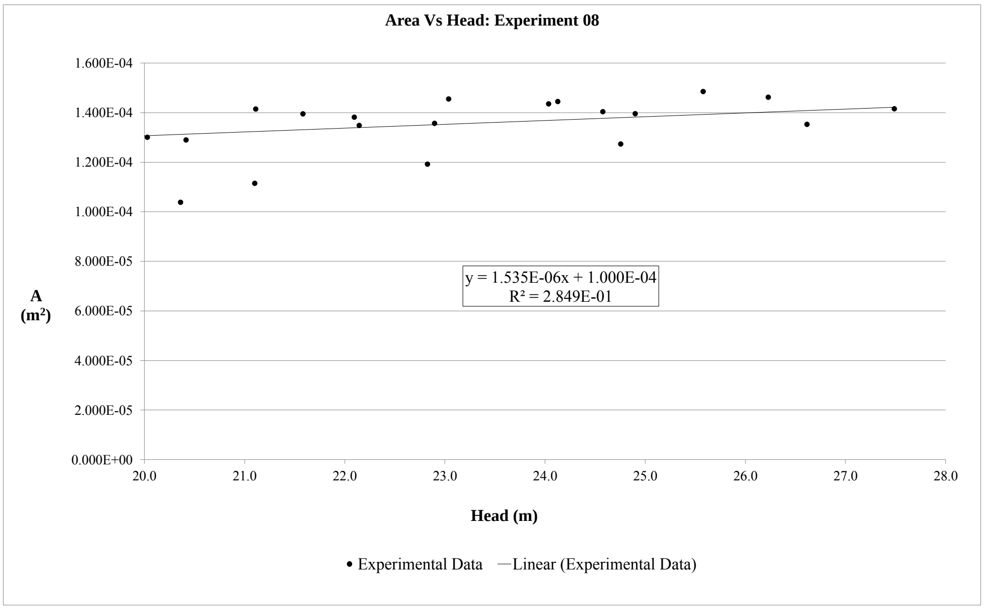
EXPERIMENTAL PARAMETERS		
1 Bar =	10.1937	m
1 l/s =	0.0010	m^3/s
g =	9.81	m/s^2
A_0 =	1.000E-04	m^2
N1 PARAMETERS		
C =	2.942E-04	
N1 =	0.7296	
R^2 =	0.78337	
SSE =	4.670E-04	
FAVAD PARAMETERS		
C_dA_0 =	1.010E-04	m^2
C_d =	1.0103	
m =	1.535E-06	
R^2 =	0.78638	
SSE =	4.682E-04	

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
1	2.0961	1.9973	2.0961E-03	20.3602	1.0487E-04	1.0380E-04	2.6523E-03	2.6506E-03
2	2.2914	2.0700	2.2914E-03	21.1009	1.1261E-04	1.1146E-04	2.7224E-03	2.7217E-03
3	2.5483	2.2393	2.5483E-03	22.8266	1.2042E-04	1.1918E-04	2.8831E-03	2.8875E-03
4	2.8352	2.4286	2.8352E-03	24.7561	1.2865E-04	1.2733E-04	3.0589E-03	3.0730E-03
5	3.1226	2.6110	3.1226E-03	26.6160	1.3665E-04	1.3525E-04	3.2250E-03	3.2523E-03
6	3.3206	2.6966	3.3206E-03	27.4878	1.4299E-04	1.4152E-04	3.3017E-03	3.3365E-03
7	3.1161	2.4428	3.1161E-03	24.9007	1.4098E-04	1.3953E-04	3.0720E-03	3.0869E-03
8	2.8391	2.1724	2.8391E-03	22.1449	1.3621E-04	1.3481E-04	2.8200E-03	2.8220E-03
9	2.6047	1.9648	2.6047E-03	20.0288	1.3140E-04	1.3005E-04	2.6207E-03	2.6187E-03
10	2.3252	1.7062	2.3252E-03	17.3925	1.2587E-04	1.2458E-04	2.3643E-03	2.3648E-03
11	2.2176	1.6172	2.2176E-03	16.4856	1.2330E-04	1.2204E-04	2.2737E-03	2.2770E-03
12	2.3701	1.7731	2.3701E-03	18.0744	1.2586E-04	1.2457E-04	2.4316E-03	2.4306E-03
13	2.6078	2.0028	2.6078E-03	20.4155	1.3030E-04	1.2897E-04	2.6576E-03	2.6559E-03
14	2.9048	2.2462	2.9048E-03	22.8971	1.3705E-04	1.3565E-04	2.8896E-03	2.8943E-03
15	3.1138	2.4110	3.1138E-03	24.5773	1.4180E-04	1.4035E-04	3.0428E-03	3.0558E-03
16	3.3509	2.5731	3.3509E-03	26.2294	1.4771E-04	1.4620E-04	3.1907E-03	3.2150E-03
17	3.1751	2.3669	3.1751E-03	24.1274	1.4593E-04	1.4444E-04	3.0021E-03	3.0125E-03
18	2.9000	2.1172	2.9000E-03	21.5825	1.4093E-04	1.3949E-04	2.7676E-03	2.7680E-03
19	2.6374	1.8883	2.6374E-03	19.2485	1.3571E-04	1.3433E-04	2.5458E-03	2.5437E-03
20	2.3572	1.6393	2.3572E-03	16.7106	1.3018E-04	1.2885E-04	2.2963E-03	2.2988E-03
21	2.2331	1.5469	2.2331E-03	15.7686	1.2696E-04	1.2566E-04	2.2011E-03	2.2073E-03
22	2.3627	1.6800	2.3627E-03	17.1254	1.2890E-04	1.2758E-04	2.3377E-03	2.3389E-03
23	2.6078	1.9055	2.6078E-03	19.4242	1.3358E-04	1.3222E-04	2.5628E-03	2.5606E-03
24	2.9057	2.1676	2.9057E-03	22.0957	1.3956E-04	1.3813E-04	2.8154E-03	2.8173E-03
25	3.1487	2.3579	3.1487E-03	24.0360	1.4499E-04	1.4351E-04	2.9938E-03	3.0037E-03
26	3.3610	2.5093	3.3610E-03	25.5789	1.5003E-04	1.4850E-04	3.1328E-03	3.1523E-03
27	3.1253	2.2600	3.1253E-03	23.0377	1.4700E-04	1.4550E-04	2.9025E-03	2.9078E-03
28	2.9084	2.0710	2.9084E-03	21.1115	1.4290E-04	1.4144E-04	2.7234E-03	2.7227E-03
29	2.5556	1.7621	2.5556E-03	17.9627	1.3613E-04	1.3474E-04	2.4206E-03	2.4198E-03
30	2.2723	1.5252	2.2723E-03	15.5472	1.3010E-04	1.2877E-04	2.1785E-03	2.1858E-03
31	2.2446	1.5200	2.2446E-03	15.4944	1.2874E-04	1.2742E-04	2.1731E-03	2.1807E-03



Experiment 08: HDPE Longitudinal 100mm

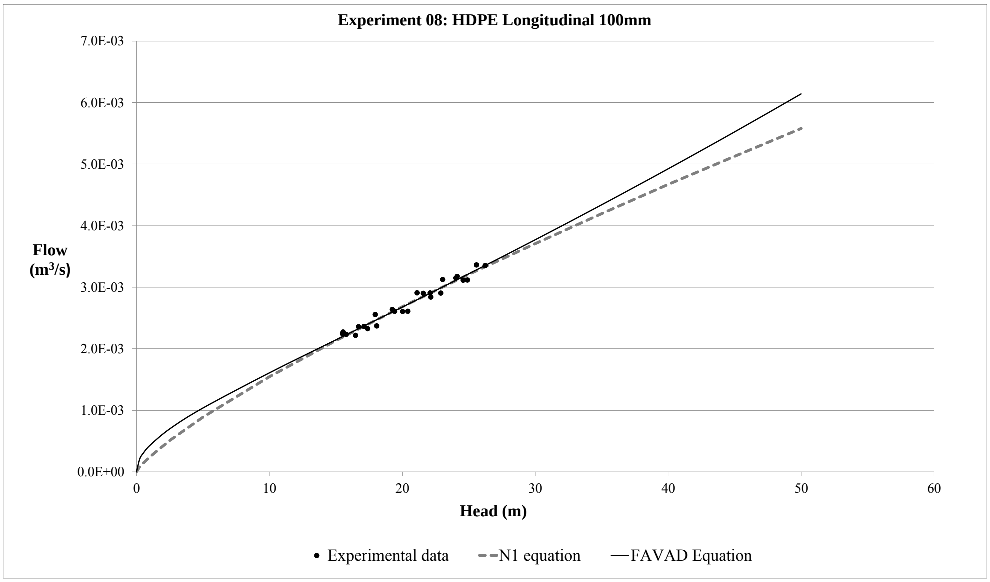




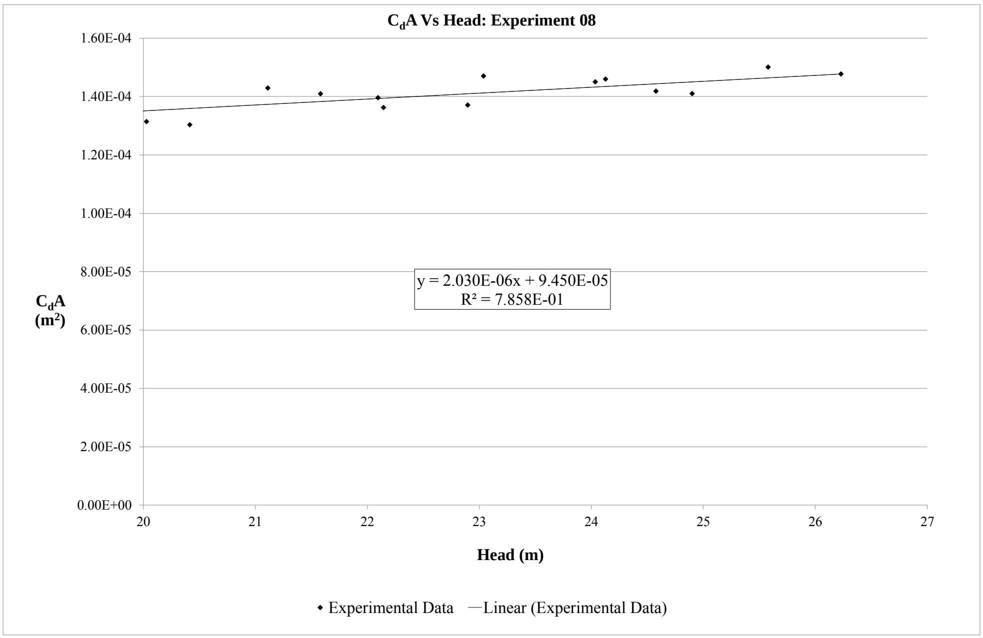
Experiment 08 (Omitted): HDPE Longitudinal 100mm

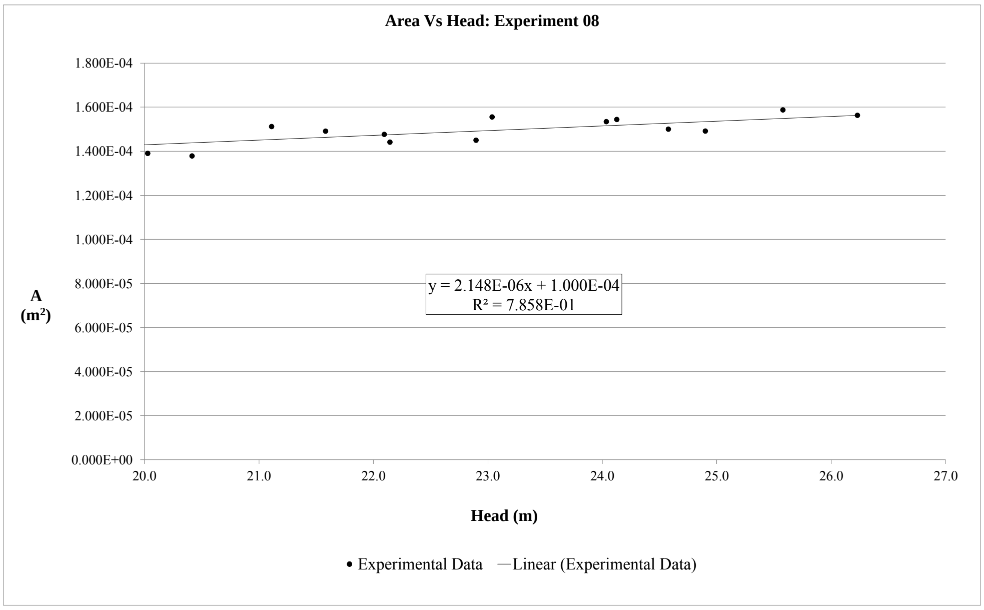
EXPERIMENTAL PARAMETERS		
1 Bar =	10.1937	m
1 l/s =	0.0010	m^3/s
g =	9.81	m/s^2
A_0 =	1.000E-04	m^2
N1 PARAMETERS		
C =	2.454E-04	
N1 =	0.7985	
R^2 =	0.96155	
SSE =	3.790E-04	
FAVAD PARAMETERS		
C_dA_0 =	9.450E-05	m^2
C_d =	0.9450	
m =	2.148E-06	
R^2 =	0.96284	
SSE =	3.792E-04	

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
7	3.1161	2.4428	3.1161E-03	24.9007	1.4098E-04	1.4917E-04	3.1965E-03	3.2063E-03
8	2.8391	2.1724	2.8391E-03	22.1449	1.3621E-04	1.4413E-04	2.9107E-03	2.9071E-03
9	2.6047	1.9648	2.6047E-03	20.0288	1.3140E-04	1.3904E-04	2.6864E-03	2.6795E-03
10	2.3252	1.7062	2.3252E-03	17.3925	1.2587E-04	1.3319E-04	2.4001E-03	2.3981E-03
11	2.2176	1.6172	2.2176E-03	16.4856	1.2330E-04	1.3047E-04	2.2996E-03	2.3016E-03
12	2.3701	1.7731	2.3701E-03	18.0744	1.2586E-04	1.3318E-04	2.4749E-03	2.4707E-03
13	2.6078	2.0028	2.6078E-03	20.4155	1.3030E-04	1.3788E-04	2.7277E-03	2.7210E-03
14	2.9048	2.2462	2.9048E-03	22.8971	1.3705E-04	1.4502E-04	2.9894E-03	2.9884E-03
15	3.1138	2.4110	3.1138E-03	24.5773	1.4180E-04	1.5004E-04	3.1633E-03	3.1710E-03
16	3.3509	2.5731	3.3509E-03	26.2294	1.4771E-04	1.5630E-04	3.3319E-03	3.3519E-03
17	3.1751	2.3669	3.1751E-03	24.1274	1.4593E-04	1.5442E-04	3.1169E-03	3.1220E-03
18	2.9000	2.1172	2.9000E-03	21.5825	1.4093E-04	1.4912E-04	2.8515E-03	2.8464E-03
19	2.6374	1.8883	2.6374E-03	19.2485	1.3571E-04	1.4361E-04	2.6025E-03	2.5960E-03
20	2.3572	1.6393	2.3572E-03	16.7106	1.3018E-04	1.3775E-04	2.3246E-03	2.3255E-03
21	2.2331	1.5469	2.2331E-03	15.7686	1.2696E-04	1.3434E-04	2.2194E-03	2.2254E-03
22	2.3627	1.6800	2.3627E-03	17.1254	1.2890E-04	1.3639E-04	2.3706E-03	2.3696E-03
23	2.6078	1.9055	2.6078E-03	19.4242	1.3358E-04	1.4135E-04	2.6214E-03	2.6148E-03
24	2.9057	2.1676	2.9057E-03	22.0957	1.3956E-04	1.4767E-04	2.9055E-03	2.9018E-03
25	3.1487	2.3579	3.1487E-03	24.0360	1.4499E-04	1.5342E-04	3.1075E-03	3.1120E-03
26	3.3610	2.5093	3.3610E-03	25.5789	1.5003E-04	1.5876E-04	3.2658E-03	3.2805E-03
27	3.1253	2.2600	3.1253E-03	23.0377	1.4700E-04	1.5555E-04	3.0040E-03	3.0036E-03
28	2.9084	2.0710	2.9084E-03	21.1115	1.4290E-04	1.5121E-04	2.8017E-03	2.7957E-03
29	2.5556	1.7621	2.5556E-03	17.9627	1.3613E-04	1.4405E-04	2.4627E-03	2.4588E-03
30	2.2723	1.5252	2.2723E-03	15.5472	1.3010E-04	1.3767E-04	2.1945E-03	2.2019E-03
31	2.2446	1.5200	2.2446E-03	15.4944	1.2874E-04	1.3622E-04	2.1885E-03	2.1962E-03



Experiment 08 (Omitted): HDPE Longitudinal 100mm

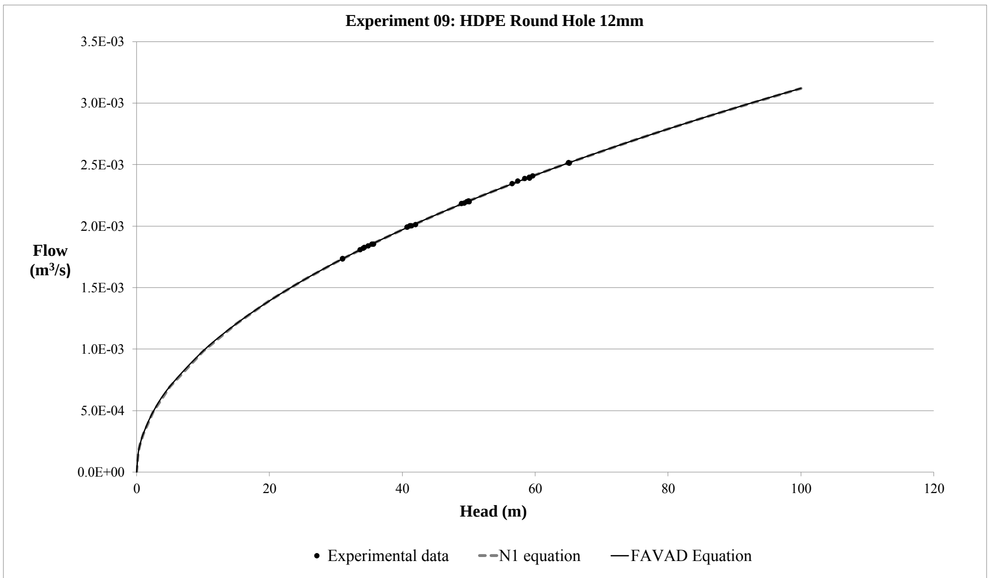




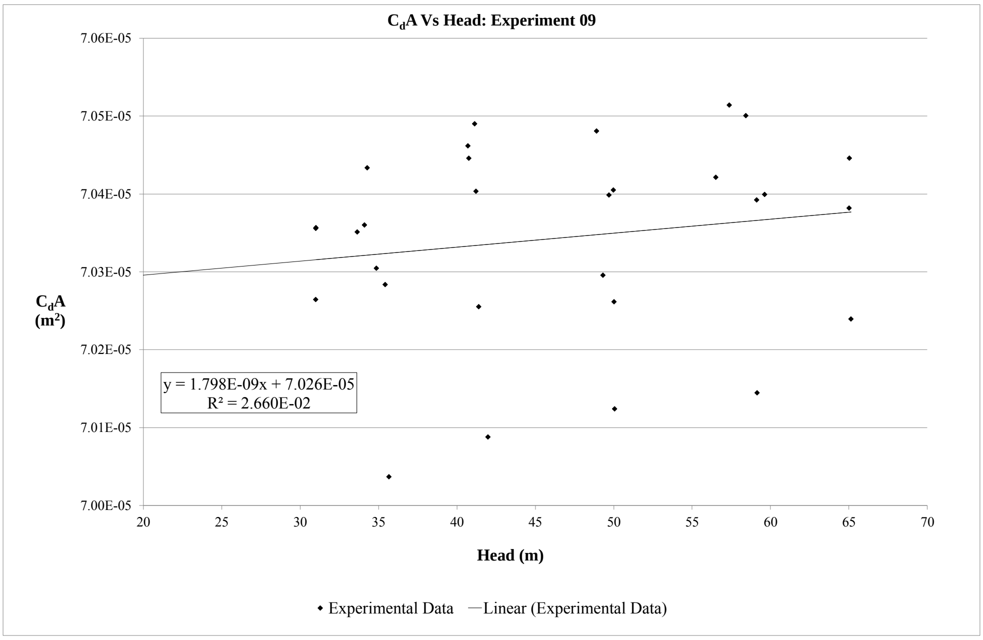
Experiment 09: HDPE Round Hole 12mm

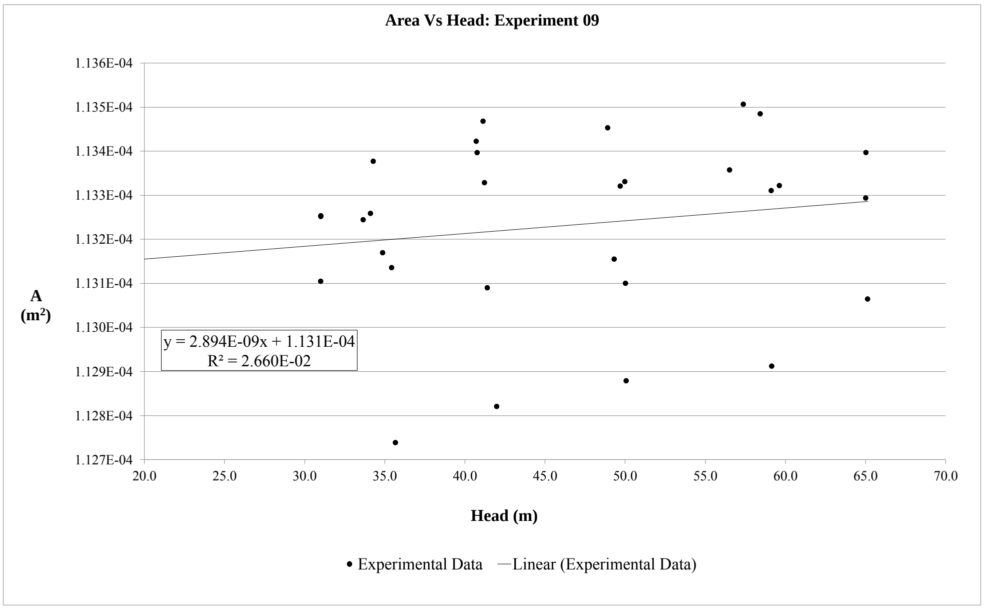
EXPERIMENTAL PARAMETERS	
1 Bar =	10.1937 m
1 l/s =	0.0010 m^3/s
g =	9.81 m/s^2
A_0 =	1.131E-04 m^2
N1 PARAMETERS	
C =	3.102E-04
N1 =	0.5012
R^2 =	0.99979
SSE =	2.702E-04
FAVAD PARAMETERS	
C_dA_0 =	7.026E-05 m^2
C_d =	0.6212
m =	2.894E-09
R^2 =	0.99979
SSE =	2.702E-04

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
1	1.8526	3.4986	1.8526E-03	35.6633	7.0037E-05	1.1274E-04	1.8602E-03	1.8602E-03
2	2.0116	4.1186	2.0116E-03	41.9834	7.0088E-05	1.1282E-04	2.0187E-03	2.0187E-03
3	2.1977	4.9110	2.1977E-03	50.0615	7.0124E-05	1.1288E-04	2.2048E-03	2.2048E-03
4	2.3895	5.8021	2.3895E-03	59.1452	7.0145E-05	1.1291E-04	2.3970E-03	2.3970E-03
5	2.5109	6.3897	2.5109E-03	65.1341	7.0239E-05	1.1306E-04	2.5157E-03	2.5158E-03
6	2.3450	5.5441	2.3450E-03	56.5152	7.0421E-05	1.1336E-04	2.3430E-03	2.3430E-03
7	2.2046	4.9028	2.2046E-03	49.9772	7.0405E-05	1.1333E-04	2.2030E-03	2.2029E-03
8	1.9912	3.9931	1.9912E-03	40.7044	7.0462E-05	1.1342E-04	1.9877E-03	1.9876E-03
9	1.8200	3.3455	1.8200E-03	34.1031	7.0360E-05	1.1326E-04	1.8190E-03	1.8190E-03
10	1.7352	3.0414	1.7352E-03	31.0028	7.0356E-05	1.1325E-04	1.7341E-03	1.7342E-03
11	1.8529	3.4752	1.8529E-03	35.4248	7.0284E-05	1.1314E-04	1.8540E-03	1.8540E-03
12	2.0021	4.0607	2.0021E-03	41.3934	7.0255E-05	1.1309E-04	2.0044E-03	2.0044E-03
13	2.2011	4.9069	2.2011E-03	50.0193	7.0262E-05	1.1310E-04	2.2039E-03	2.2038E-03
14	2.3973	5.7993	2.3973E-03	59.1161	7.0392E-05	1.1331E-04	2.3964E-03	2.3964E-03
15	2.5137	6.3779	2.5137E-03	65.0146	7.0382E-05	1.1329E-04	2.5134E-03	2.5135E-03
16	2.3870	5.7317	2.3870E-03	58.4274	7.0500E-05	1.1348E-04	2.3824E-03	2.3824E-03
17	2.1982	4.8752	2.1982E-03	49.6959	7.0399E-05	1.1332E-04	2.1968E-03	2.1967E-03
18	2.0025	4.0352	2.0025E-03	41.1333	7.0490E-05	1.1347E-04	1.9981E-03	1.9981E-03
19	1.8266	3.3628	1.8266E-03	34.2789	7.0434E-05	1.1338E-04	1.8237E-03	1.8237E-03
20	1.7354	3.0421	1.7354E-03	31.0099	7.0357E-05	1.1325E-04	1.7343E-03	1.7344E-03
21	1.8387	3.4200	1.8387E-03	34.8624	7.0305E-05	1.1317E-04	1.8392E-03	1.8392E-03
22	2.0021	4.0434	2.0021E-03	41.2176	7.0403E-05	1.1333E-04	2.0002E-03	2.0001E-03
23	2.1866	4.8379	2.1866E-03	49.3163	7.0296E-05	1.1316E-04	2.1883E-03	2.1883E-03
24	2.4079	5.8493	2.4079E-03	59.6257	7.0399E-05	1.1332E-04	2.4067E-03	2.4068E-03
25	2.5163	6.3793	2.5163E-03	65.0286	7.0446E-05	1.1340E-04	2.5137E-03	2.5138E-03
26	2.3658	5.6283	2.3658E-03	57.3728	7.0514E-05	1.1351E-04	2.3607E-03	2.3607E-03
27	2.1833	4.7979	2.1833E-03	48.9086	7.0481E-05	1.1345E-04	2.1792E-03	2.1792E-03
28	1.9922	3.9986	1.9922E-03	40.7607	7.0446E-05	1.1340E-04	1.9890E-03	1.9890E-03
29	1.8075	3.3007	1.8075E-03	33.6462	7.0351E-05	1.1324E-04	1.8067E-03	1.8067E-03
30	1.7328	3.0407	1.7328E-03	30.9958	7.0264E-05	1.1310E-04	1.7339E-03	1.7340E-03



Experiment 09: HDPE Round Hole 12mm

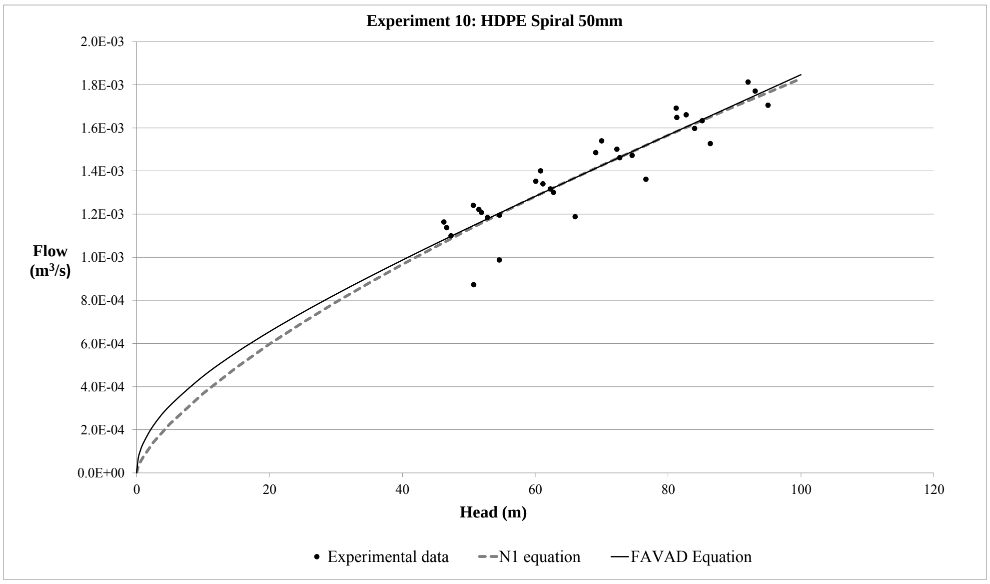




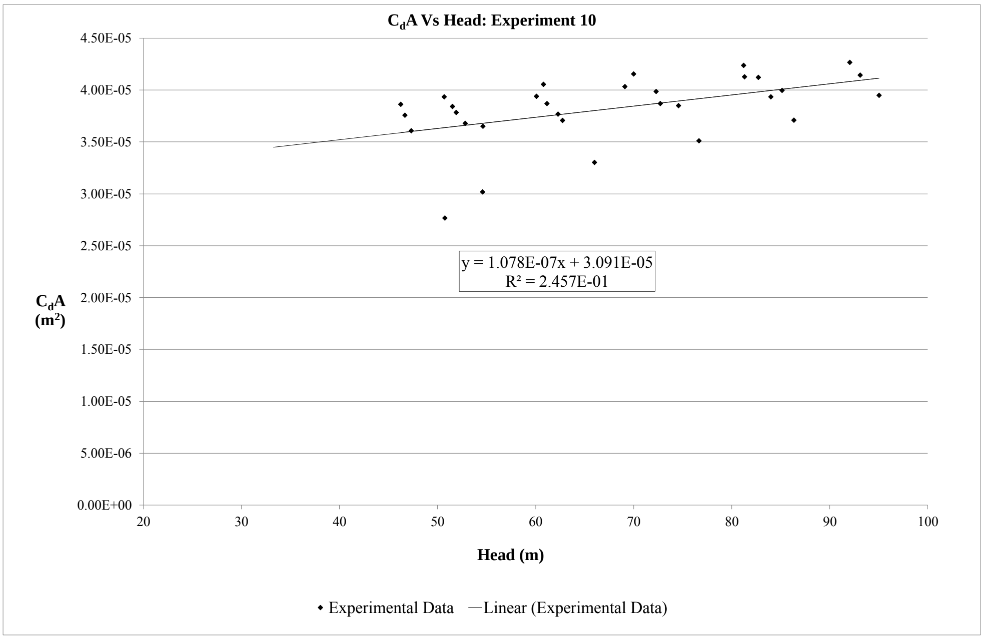
Experiment 10: HDPE Spiral 50mm

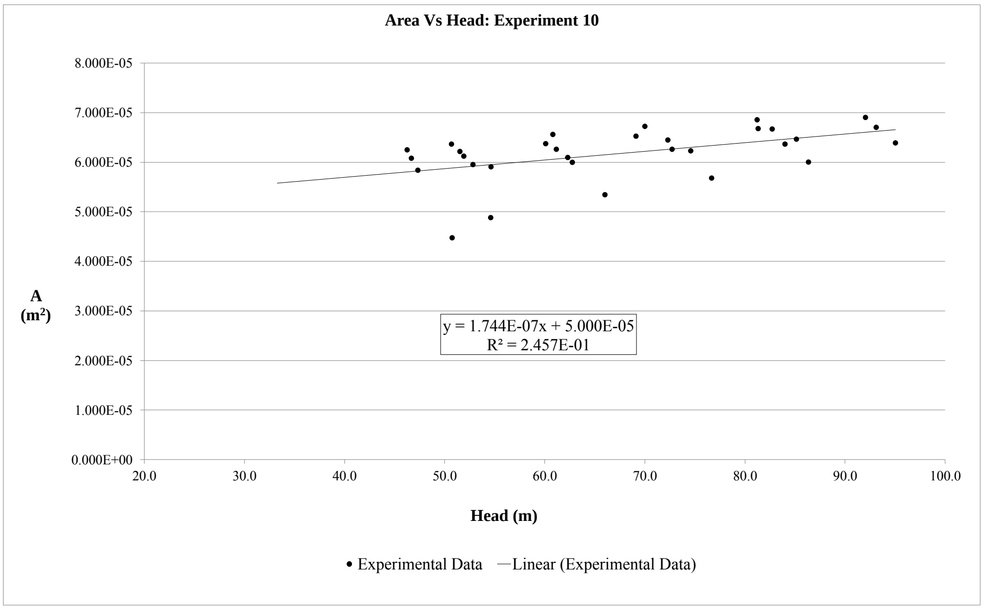
EXPERIMENTAL PARAMETERS		
1 Bar =	10.1937	m
1 l/s =	0.0010	m^3/s
g =	9.81	m/s^2
A_0 =	5.000E-05	m^2
N1 PARAMETERS		
C =	7.426E-05	
N1 =	0.6956	
R^2 =	0.82732	
SSE =	1.224E-04	
FAVAD PARAMETERS		
C_dA_0 =	3.091E-05	m^2
C_d =	0.6181	
m =	1.744E-07	
R^2 =	0.82749	
SSE =	1.228E-04	

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
1	0.8728	4.9786	8.7281E-04	50.7505	2.7660E-05	4.4748E-05	1.1404E-03	1.1479E-03
2	0.9875	5.3564	9.8752E-04	54.6017	3.0171E-05	4.8811E-05	1.2000E-03	1.2043E-03
3	1.1884	6.4757	1.1884E-03	66.0114	3.3022E-05	5.3423E-05	1.3693E-03	1.3684E-03
4	1.3615	7.5214	1.3615E-03	76.6705	3.5103E-05	5.6790E-05	1.5195E-03	1.5193E-03
5	1.5267	8.4710	1.5267E-03	86.3510	3.7092E-05	6.0007E-05	1.6506E-03	1.6554E-03
6	1.7050	9.3234	1.7050E-03	95.0402	3.9483E-05	6.3876E-05	1.7644E-03	1.7771E-03
7	1.5971	8.2407	1.5971E-03	84.0032	3.9339E-05	6.3643E-05	1.6192E-03	1.6224E-03
8	1.4615	7.1345	1.4615E-03	72.7266	3.8692E-05	6.2596E-05	1.4647E-03	1.4637E-03
9	1.3170	6.1110	1.3170E-03	62.2939	3.7670E-05	6.0943E-05	1.3152E-03	1.3153E-03
10	1.1843	5.1821	1.1843E-03	52.8244	3.6787E-05	5.9514E-05	1.1727E-03	1.1783E-03
11	1.0992	4.6428	1.0992E-03	47.3268	3.6073E-05	5.8359E-05	1.0864E-03	1.0973E-03
12	1.1951	5.3593	1.1951E-03	54.6311	3.6505E-05	5.9058E-05	1.2004E-03	1.2047E-03
13	1.3004	6.1559	1.3004E-03	62.7509	3.7061E-05	5.9957E-05	1.3219E-03	1.3219E-03
14	1.4725	7.3166	1.4725E-03	74.5826	3.8494E-05	6.2275E-05	1.4906E-03	1.4899E-03
15	1.6330	8.3524	1.6330E-03	85.1418	3.9954E-05	6.4638E-05	1.6345E-03	1.6384E-03
16	1.7707	9.1345	1.7707E-03	93.1140	4.1427E-05	6.7021E-05	1.7394E-03	1.7501E-03
17	1.6483	7.9772	1.6483E-03	81.3174	4.1267E-05	6.6763E-05	1.5830E-03	1.5847E-03
18	1.4851	6.7800	1.4851E-03	69.1131	4.0329E-05	6.5244E-05	1.4137E-03	1.4125E-03
19	1.3524	5.8952	1.3524E-03	60.0935	3.9386E-05	6.3718E-05	1.2827E-03	1.2837E-03
20	1.2213	5.0545	1.2213E-03	51.5238	3.8413E-05	6.2145E-05	1.1525E-03	1.1593E-03
21	1.1370	4.5793	1.1370E-03	46.6800	3.7572E-05	6.0784E-05	1.0760E-03	1.0876E-03
22	1.2074	5.0924	1.2074E-03	51.9104	3.7834E-05	6.1209E-05	1.1585E-03	1.1650E-03
23	1.3403	6.0000	1.3403E-03	61.1621	3.8691E-05	6.2594E-05	1.2985E-03	1.2991E-03
24	1.5009	7.0924	1.5009E-03	72.2978	3.9851E-05	6.4471E-05	1.4587E-03	1.4576E-03
25	1.6604	8.1152	1.6604E-03	82.7235	4.1213E-05	6.6675E-05	1.6020E-03	1.6045E-03
26	1.8129	9.0297	1.8129E-03	92.0454	4.2659E-05	6.9014E-05	1.7255E-03	1.7352E-03
27	1.6913	7.9676	1.6913E-03	81.2190	4.2369E-05	6.8546E-05	1.5817E-03	1.5833E-03
28	1.5397	6.8676	1.5397E-03	70.0060	4.1546E-05	6.7213E-05	1.4264E-03	1.4252E-03
29	1.4005	5.9655	1.4005E-03	60.8106	4.0545E-05	6.5594E-05	1.2933E-03	1.2940E-03
30	1.2406	4.9724	1.2406E-03	50.6872	3.9339E-05	6.3642E-05	1.1394E-03	1.1470E-03
31	1.1635	4.5372	1.1635E-03	46.2512	3.8622E-05	6.2483E-05	1.0691E-03	1.0812E-03



Experiment 10: HDPE Spiral 50mm

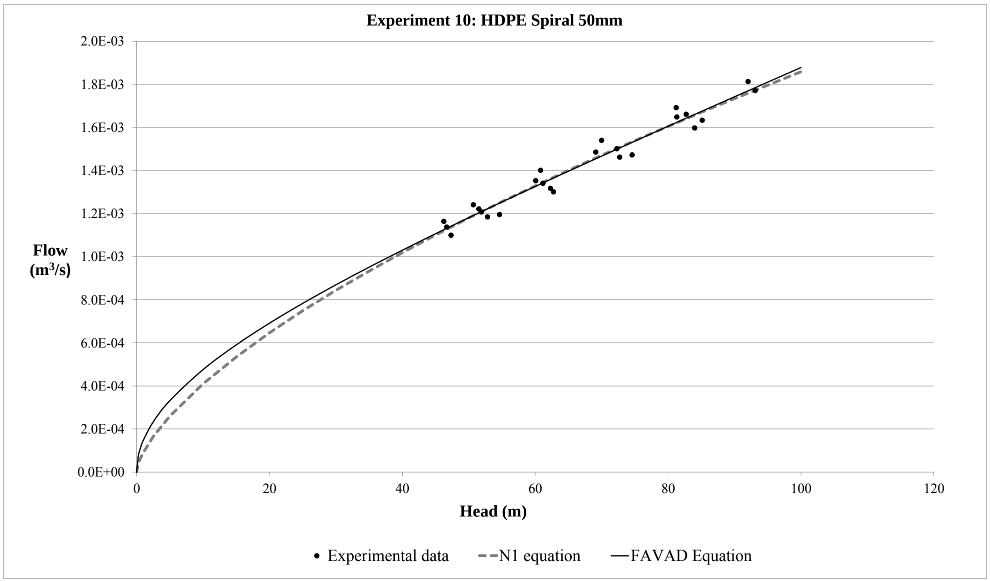




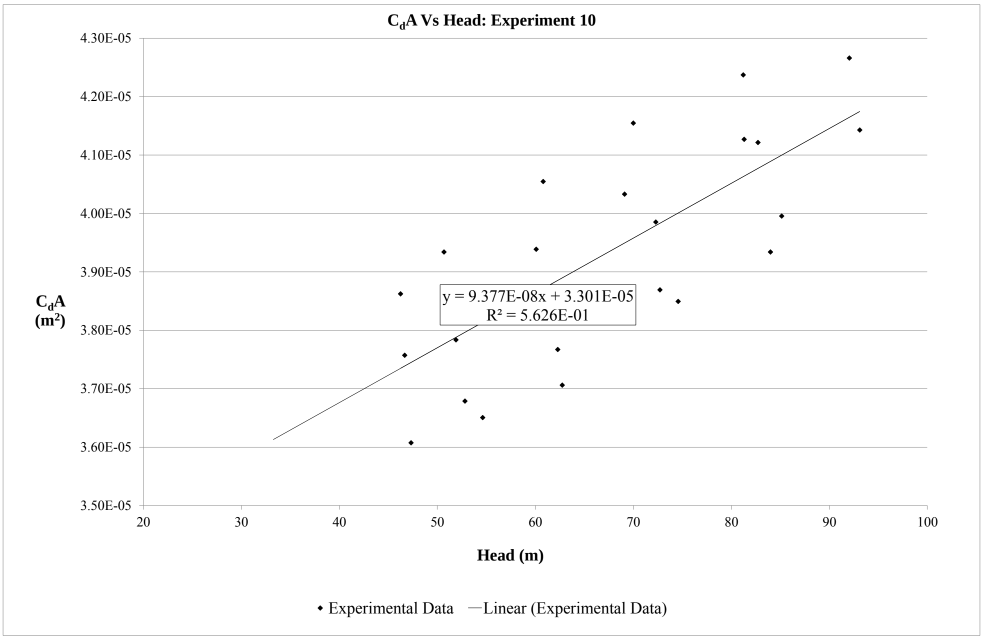
Experiment 10 (Omitted): HDPE Spiral 50mm

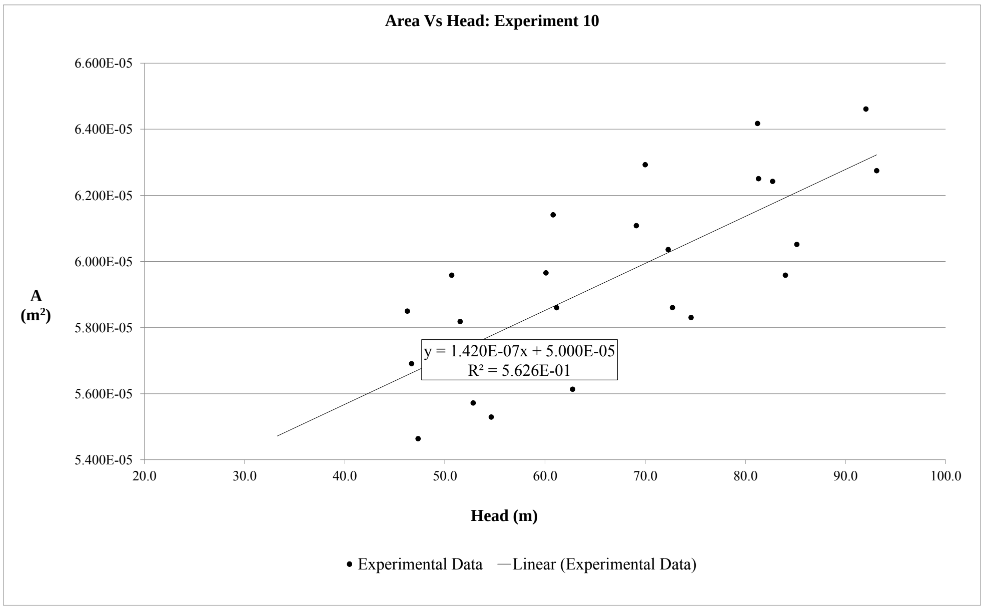
EXPERIMENTAL PARAMETERS	
1 Bar =	10.1937 m
1 l/s =	0.0010 m^3/s
g =	9.81 m/s^2
A_0 =	5.000E-05 m^2
N1 PARAMETERS	
C =	9.045E-05
N1 =	0.6563
R^2 =	0.95647
SSE =	1.025E-04
FAVAD PARAMETERS	
C_dA_0 =	3.301E-05 m^2
C_d =	0.6602
m =	1.420E-07
R^2 =	0.95727
SSE =	1.025E-04

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
7	1.5971	8.2407	1.5971E-03	84.0032	3.9339E-05	5.9583E-05	1.6570E-03	1.6600E-03
8	1.4615	7.1345	1.4615E-03	72.7266	3.8692E-05	5.8602E-05	1.5074E-03	1.5046E-03
9	1.3170	6.1110	1.3170E-03	62.2939	3.7670E-05	5.7055E-05	1.3617E-03	1.3583E-03
10	1.1843	5.1821	1.1843E-03	52.8244	3.6787E-05	5.5717E-05	1.2221E-03	1.2222E-03
11	1.0992	4.6428	1.0992E-03	47.3268	3.6073E-05	5.4636E-05	1.1370E-03	1.1412E-03
12	1.1951	5.3593	1.1951E-03	54.6311	3.6505E-05	5.5290E-05	1.2493E-03	1.2485E-03
13	1.3004	6.1559	1.3004E-03	62.7509	3.7061E-05	5.6132E-05	1.3683E-03	1.3648E-03
14	1.4725	7.3166	1.4725E-03	74.5826	3.8494E-05	5.8302E-05	1.5325E-03	1.5303E-03
15	1.6330	8.3524	1.6330E-03	85.1418	3.9954E-05	6.0514E-05	1.6717E-03	1.6756E-03
16	1.7707	9.1345	1.7707E-03	93.1140	4.1427E-05	6.2745E-05	1.7728E-03	1.7842E-03
17	1.6483	7.9772	1.6483E-03	81.3174	4.1267E-05	6.2503E-05	1.6220E-03	1.6232E-03
18	1.4851	6.7800	1.4851E-03	69.1131	4.0329E-05	6.1082E-05	1.4578E-03	1.4543E-03
19	1.3524	5.8952	1.3524E-03	60.0935	3.9386E-05	5.9653E-05	1.3300E-03	1.3270E-03
20	1.2213	5.0545	1.2213E-03	51.5238	3.8413E-05	5.8180E-05	1.2022E-03	1.2032E-03
21	1.1370	4.5793	1.1370E-03	46.6800	3.7572E-05	5.6906E-05	1.1268E-03	1.1315E-03
22	1.2074	5.0924	1.2074E-03	51.9104	3.7834E-05	5.7304E-05	1.2081E-03	1.2089E-03
23	1.3403	6.0000	1.3403E-03	61.1621	3.8691E-05	5.8601E-05	1.3455E-03	1.3422E-03
24	1.5009	7.0924	1.5009E-03	72.2978	3.9851E-05	6.0358E-05	1.5016E-03	1.4987E-03
25	1.6604	8.1152	1.6604E-03	82.7235	4.1213E-05	6.2422E-05	1.6404E-03	1.6425E-03
26	1.8129	9.0297	1.8129E-03	92.0454	4.2659E-05	6.4611E-05	1.7594E-03	1.7697E-03
27	1.6913	7.9676	1.6913E-03	81.2190	4.2369E-05	6.4173E-05	1.6207E-03	1.6218E-03
28	1.5397	6.8676	1.5397E-03	70.0060	4.1546E-05	6.2925E-05	1.4702E-03	1.4667E-03
29	1.4005	5.9655	1.4005E-03	60.8106	4.0545E-05	6.1409E-05	1.3404E-03	1.3372E-03
30	1.2406	4.9724	1.2406E-03	50.6872	3.9339E-05	5.9582E-05	1.1894E-03	1.1909E-03
31	1.1635	4.5372	1.1635E-03	46.2512	3.8622E-05	5.8497E-05	1.1200E-03	1.1251E-03



Experiment 10 (Omitted): HDPE Spiral 50mm

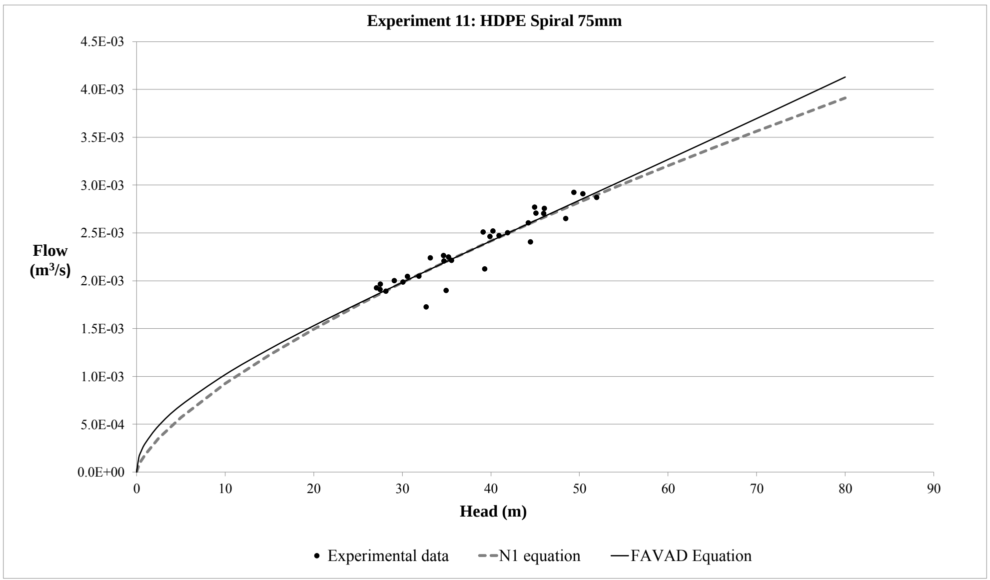




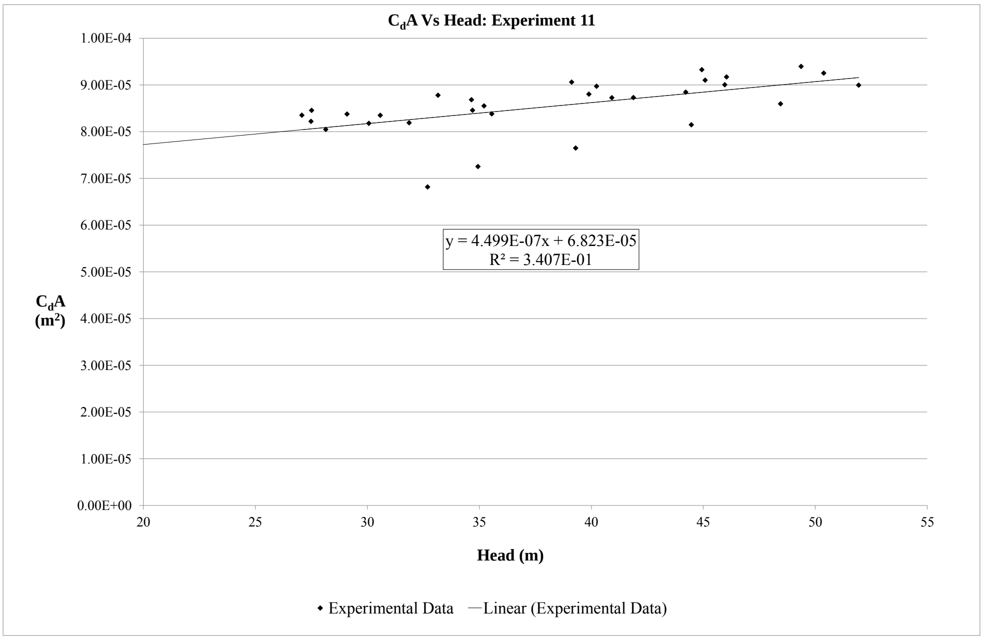
Experiment 11: HDPE Spiral 73mm

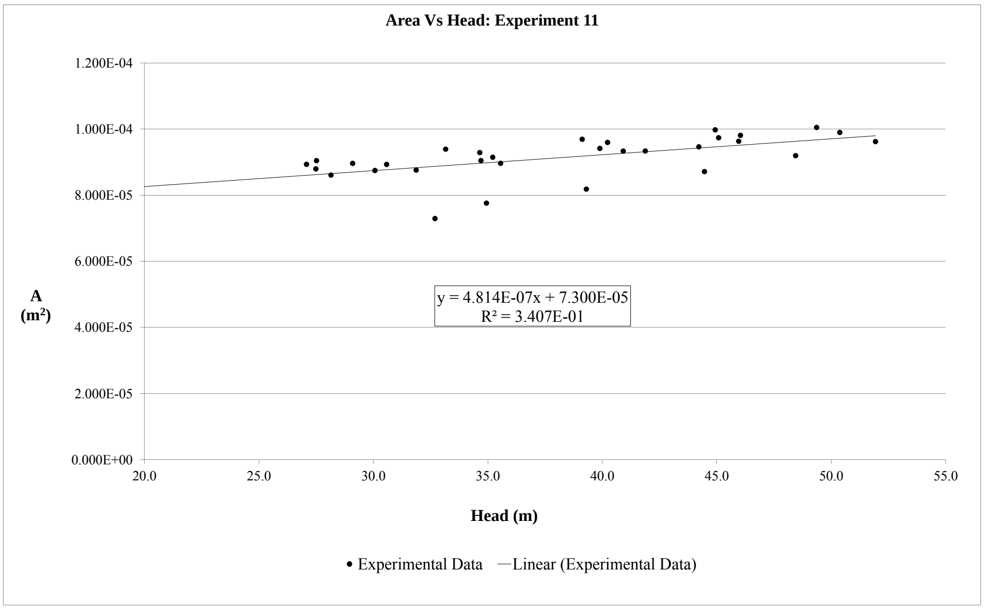
EXPERIMENTAL PARAMETERS	
1 Bar =	10.1937 m
1 l/s =	0.0010 m^3/s
g =	9.81 m/s^2
A_0 =	7.300E-05 m^2
N1 PARAMETERS	
C =	1.873E-04
N1 =	0.6934
R^2 =	0.86706
SSE =	3.448E-04
FAVAD PARAMETERS	
C_dA_0 =	6.823E-05 m^2
C_d =	0.9346
m =	4.814E-07
R^2 =	0.86942
SSE =	3.454E-04

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
1	1.7264	3.2073	1.7264E-03	32.6945	6.8165E-05	7.2933E-05	2.1020E-03	2.1006E-03
2	1.8985	3.4276	1.8985E-03	34.9397	7.2512E-05	7.7584E-05	2.2010E-03	2.1979E-03
3	2.1236	3.8557	2.1236E-03	39.3039	7.6473E-05	8.1823E-05	2.3882E-03	2.3857E-03
4	2.4058	4.3621	2.4058E-03	44.4663	8.1451E-05	8.7149E-05	2.6015E-03	2.6061E-03
5	2.6500	4.7529	2.6500E-03	48.4491	8.5950E-05	9.1962E-05	2.7610E-03	2.7756E-03
6	2.8706	5.0950	2.8706E-03	51.9368	8.9927E-05	9.6218E-05	2.8973E-03	2.9239E-03
7	2.6050	4.3379	2.6050E-03	44.2195	8.8441E-05	9.4627E-05	2.5915E-03	2.5956E-03
8	2.4719	4.0141	2.4719E-03	40.9182	8.7243E-05	9.3345E-05	2.4558E-03	2.4548E-03
9	2.2062	3.4041	2.2062E-03	34.7007	8.4554E-05	9.0469E-05	2.1906E-03	2.1876E-03
10	1.9861	2.9500	1.9861E-03	30.0714	8.1767E-05	8.7487E-05	1.9835E-03	1.9859E-03
11	1.8909	2.7613	1.8909E-03	28.1481	8.0464E-05	8.6092E-05	1.8947E-03	1.9010E-03
12	2.0474	3.1264	2.0474E-03	31.8698	8.1878E-05	8.7605E-05	2.0651E-03	2.0646E-03
13	2.2132	3.4883	2.2132E-03	35.5584	8.3791E-05	8.9653E-05	2.2280E-03	2.2247E-03
14	2.5017	4.1086	2.5017E-03	41.8815	8.7271E-05	9.3375E-05	2.4957E-03	2.4959E-03
15	2.7032	4.5087	2.7032E-03	45.9599	9.0022E-05	9.6319E-05	2.6618E-03	2.6697E-03
16	2.9087	4.9421	2.9087E-03	50.3779	9.2518E-05	9.8990E-05	2.8367E-03	2.8576E-03
17	2.7560	4.5163	2.7560E-03	46.0377	9.1699E-05	9.8114E-05	2.6649E-03	2.6730E-03
18	2.5200	3.9469	2.5200E-03	40.2334	8.9693E-05	9.5967E-05	2.4272E-03	2.4255E-03
19	2.2636	3.3993	2.2636E-03	34.6512	8.6814E-05	9.2887E-05	2.1884E-03	2.1855E-03
20	2.0013	2.8543	2.0013E-03	29.0957	8.3761E-05	8.9621E-05	1.9387E-03	1.9429E-03
21	1.9087	2.6966	1.9087E-03	27.4878	8.2191E-05	8.7941E-05	1.8638E-03	1.8716E-03
22	2.0449	3.0000	2.0449E-03	30.5810	8.3483E-05	8.9323E-05	2.0068E-03	2.0082E-03
23	2.2474	3.4545	2.2474E-03	35.2139	8.5501E-05	9.1482E-05	2.2130E-03	2.2098E-03
24	2.4621	3.9136	2.4621E-03	39.8937	8.8006E-05	9.4162E-05	2.4130E-03	2.4109E-03
25	2.7066	4.4228	2.7066E-03	45.0842	9.1005E-05	9.7372E-05	2.6265E-03	2.6324E-03
26	2.9235	4.8429	2.9235E-03	49.3665	9.3938E-05	1.0051E-04	2.7971E-03	2.8146E-03
27	2.7686	4.4083	2.7686E-03	44.9366	9.3242E-05	9.9764E-05	2.6206E-03	2.6262E-03
28	2.5096	3.8379	2.5096E-03	39.1226	9.0582E-05	9.6918E-05	2.3805E-03	2.3779E-03
29	2.2389	3.2529	2.2389E-03	33.1586	8.7778E-05	9.3918E-05	2.1226E-03	2.1207E-03
30	1.9644	2.6993	1.9644E-03	27.5161	8.4544E-05	9.0458E-05	1.8651E-03	1.8729E-03
31	1.9249	2.6566	1.9249E-03	27.0800	8.3509E-05	8.9350E-05	1.8446E-03	1.8535E-03



Experiment 11: HDPE Spiral 73mm

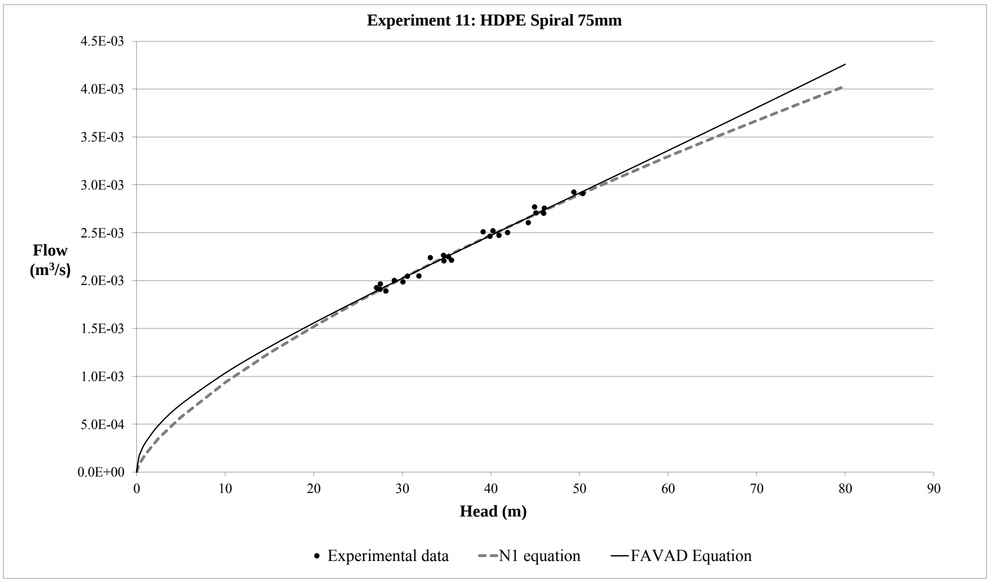




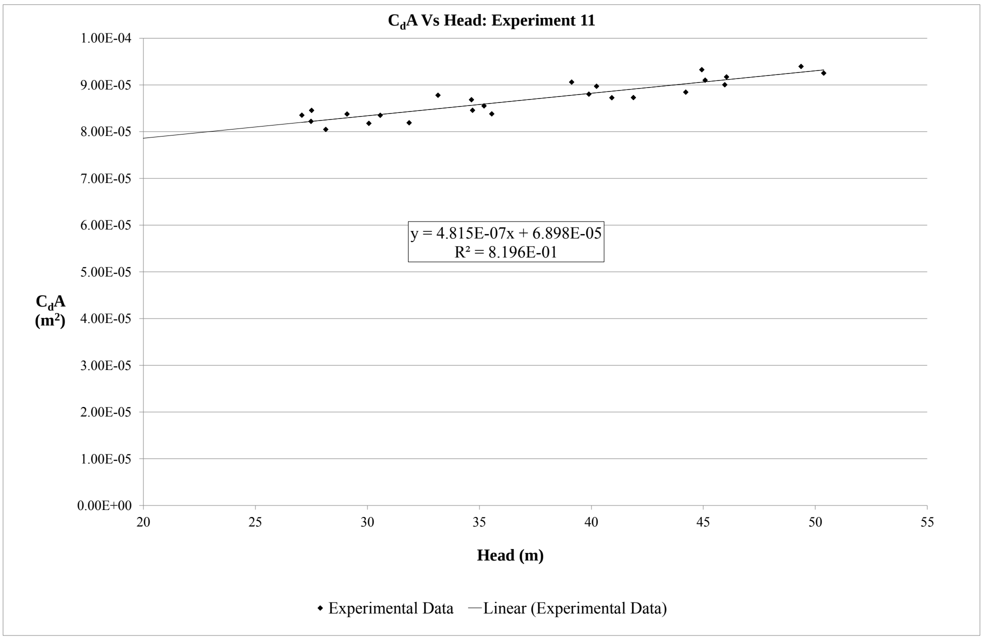
Experiment 11 (Omitted): HDPE Spiral 73mm

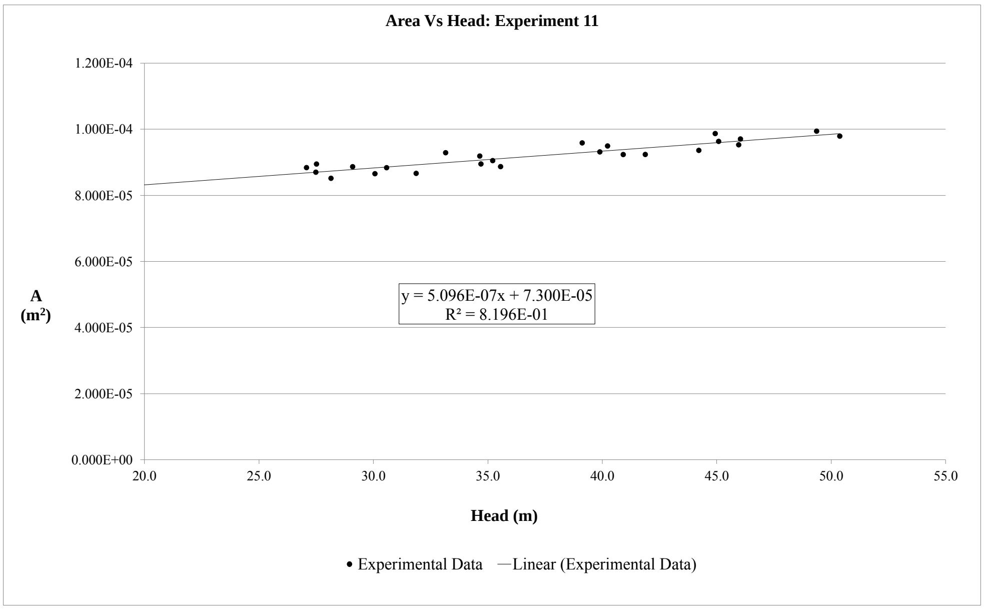
EXPERIMENTAL PARAMETERS	
1 Bar =	10.1937 m
1 l/s =	0.0010 m^3/s
g =	9.81 m/s^2
A_0 =	7.300E-05 m^2
N1 PARAMETERS	
C =	1.855E-04
N1 =	0.7026
R^2 =	0.98129
SSE =	2.815E-04
FAVAD PARAMETERS	
C_dA_0 =	6.898E-05 m^2
C_d =	0.9449
m =	5.096E-07
R^2 =	0.98215
SSE =	2.816E-04

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
7	2.6050	4.3379	2.6050E-03	44.2195	8.8441E-05	9.3601E-05	2.6581E-03	2.6588E-03
8	2.4719	4.0141	2.4719E-03	40.9182	8.7243E-05	9.2333E-05	2.5171E-03	2.5126E-03
9	2.2062	3.4041	2.2062E-03	34.7007	8.4554E-05	8.9487E-05	2.2418E-03	2.2357E-03
10	1.9861	2.9500	1.9861E-03	30.0714	8.1767E-05	8.6537E-05	2.0273E-03	2.0271E-03
11	1.8909	2.7613	1.8909E-03	28.1481	8.0464E-05	8.5158E-05	1.9353E-03	1.9394E-03
12	2.0474	3.1264	2.0474E-03	31.8698	8.1878E-05	8.6654E-05	2.1117E-03	2.1085E-03
13	2.2132	3.4883	2.2132E-03	35.5584	8.3791E-05	8.8680E-05	2.2806E-03	2.2741E-03
14	2.5017	4.1086	2.5017E-03	41.8815	8.7271E-05	9.2362E-05	2.5585E-03	2.5553E-03
15	2.7032	4.5087	2.7032E-03	45.9599	9.0022E-05	9.5274E-05	2.7312E-03	2.7358E-03
16	2.9087	4.9421	2.9087E-03	50.3779	9.2518E-05	9.7916E-05	2.9131E-03	2.9311E-03
17	2.7560	4.5163	2.7560E-03	46.0377	9.1699E-05	9.7049E-05	2.7344E-03	2.7392E-03
18	2.5200	3.9469	2.5200E-03	40.2334	8.9693E-05	9.4926E-05	2.4874E-03	2.4822E-03
19	2.2636	3.3993	2.2636E-03	34.6512	8.6814E-05	9.1879E-05	2.2396E-03	2.2335E-03
20	2.0013	2.8543	2.0013E-03	29.0957	8.3761E-05	8.8648E-05	1.9808E-03	1.9827E-03
21	1.9087	2.6966	1.9087E-03	27.4878	8.2191E-05	8.6986E-05	1.9033E-03	1.9092E-03
22	2.0449	3.0000	2.0449E-03	30.5810	8.3483E-05	8.8354E-05	2.0513E-03	2.0502E-03
23	2.2474	3.4545	2.2474E-03	35.2139	8.5501E-05	9.0489E-05	2.2651E-03	2.2587E-03
24	2.4621	3.9136	2.4621E-03	39.8937	8.8006E-05	9.3140E-05	2.4726E-03	2.4671E-03
25	2.7066	4.4228	2.7066E-03	45.0842	9.1005E-05	9.6315E-05	2.6945E-03	2.6970E-03
26	2.9235	4.8429	2.9235E-03	49.3665	9.3938E-05	9.9418E-05	2.8719E-03	2.8864E-03
27	2.7686	4.4083	2.7686E-03	44.9366	9.3242E-05	9.8682E-05	2.6883E-03	2.6905E-03
28	2.5096	3.8379	2.5096E-03	39.1226	9.0582E-05	9.5867E-05	2.4389E-03	2.4329E-03
29	2.2389	3.2529	2.2389E-03	33.1586	8.7778E-05	9.2899E-05	2.1713E-03	2.1665E-03
30	1.9644	2.6993	1.9644E-03	27.5161	8.4544E-05	8.9477E-05	1.9046E-03	1.9105E-03
31	1.9249	2.6566	1.9249E-03	27.0800	8.3509E-05	8.8381E-05	1.8834E-03	1.8904E-03



Experiment 11 (Omitted): HDPE Spiral 73mm

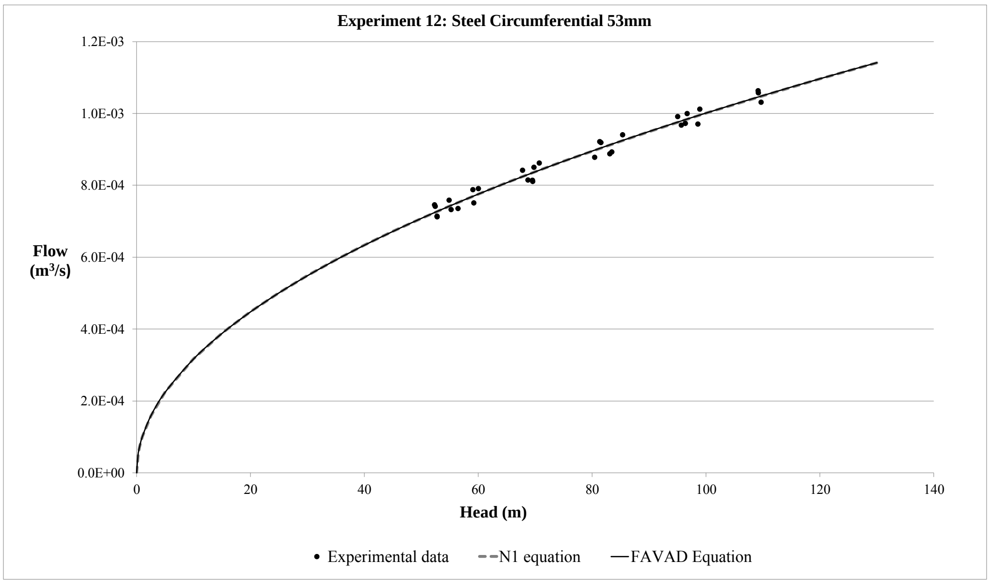




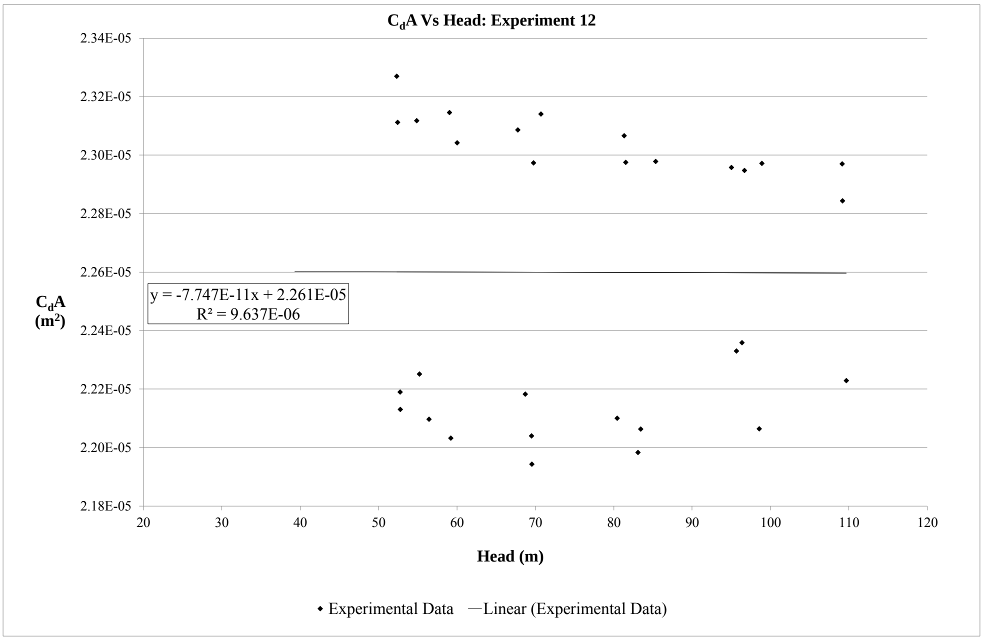
Experiment 12: Steel Circumferential 53mm

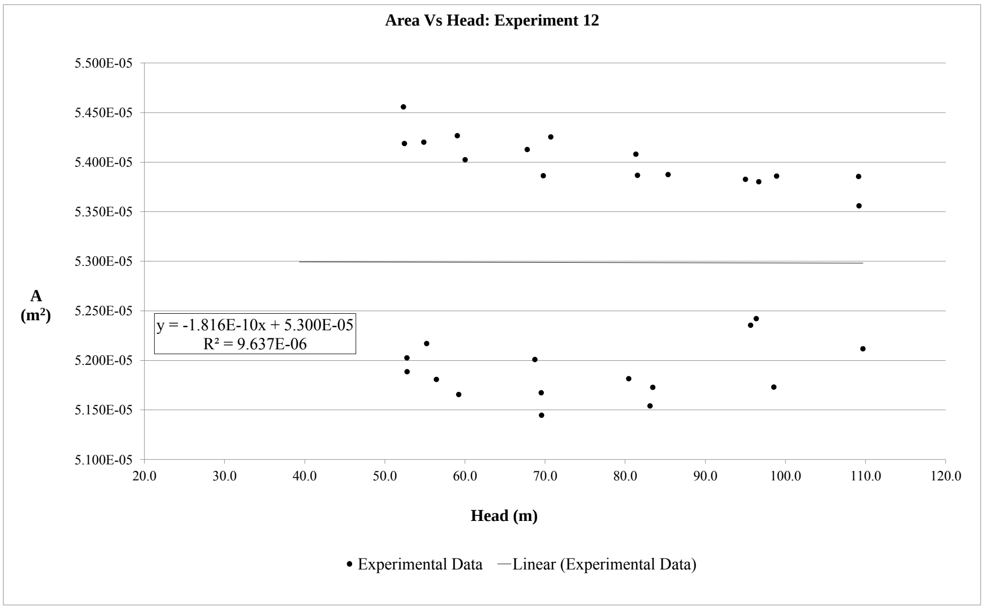
EXPERIMENTAL PARAMETERS	
1 Bar =	10.1937 m
1 l/s =	0.0010 m^3/s
g =	9.81 m/s^2
A_0 =	5.300E-05 m^2
N1 PARAMETERS	
C =	1.005E-04
N1 =	0.4991
R^2 =	0.97358
SSE =	4.761E-05
FAVAD PARAMETERS	
C_dA_0 =	2.261E-05 m^2
C_d =	0.4265
m =	-1.816E-10
R^2 =	0.97358
SSE =	4.762E-05

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
1	0.7456	5.1336	7.4561E-04	52.3300	2.3270E-05	5.4557E-05	7.2423E-04	7.2421E-04
2	0.7879	5.7933	7.8785E-04	59.0554	2.3145E-05	5.4266E-05	7.6927E-04	7.6932E-04
3	0.8620	6.9378	8.6198E-04	70.7215	2.3140E-05	5.4254E-05	8.4170E-04	8.4185E-04
4	0.9404	8.3738	9.4036E-04	85.3603	2.2978E-05	5.3874E-05	9.2456E-04	9.2484E-04
5	1.0119	9.7028	1.0119E-03	98.9068	2.2972E-05	5.3859E-05	9.9508E-04	9.9548E-04
6	1.0629	10.7071	1.0629E-03	109.1452	2.2970E-05	5.3854E-05	1.0452E-03	1.0457E-03
7	0.9913	9.3214	9.9126E-04	95.0192	2.2958E-05	5.3826E-05	9.7537E-04	9.7573E-04
8	0.9215	7.9793	9.2145E-04	81.3385	2.3066E-05	5.4080E-05	9.0255E-04	9.0280E-04
9	0.8419	6.6490	8.4187E-04	67.7774	2.3086E-05	5.4127E-05	8.2402E-04	8.2415E-04
10	0.7586	5.3834	7.5856E-04	54.8771	2.3118E-05	5.4201E-05	7.4161E-04	7.4162E-04
11	0.7414	5.1453	7.4141E-04	52.4499	2.3112E-05	5.4187E-05	7.2505E-04	7.2504E-04
12	0.7908	5.8890	7.9078E-04	60.0302	2.3042E-05	5.4023E-05	7.7559E-04	7.7564E-04
13	0.8500	6.8455	8.5004E-04	69.7810	2.2973E-05	5.3862E-05	8.3609E-04	8.3624E-04
14	0.9190	7.9993	9.1896E-04	81.5422	2.2975E-05	5.3866E-05	9.0368E-04	9.0393E-04
15	0.9994	9.4847	9.9945E-04	96.6837	2.2947E-05	5.3801E-05	9.8386E-04	9.8423E-04
16	1.0573	10.7114	1.0573E-03	109.1889	2.2844E-05	5.3558E-05	1.0454E-03	1.0459E-03
17	0.9722	9.4536	9.7220E-04	96.3667	2.2359E-05	5.2421E-05	9.8225E-04	9.8262E-04
18	0.8927	8.1862	8.9273E-04	83.4476	2.2063E-05	5.1728E-05	9.1416E-04	9.1443E-04
19	0.8140	6.8200	8.1398E-04	69.5209	2.2040E-05	5.1673E-05	8.3453E-04	8.3468E-04
20	0.7353	5.5372	7.3535E-04	56.4449	2.2097E-05	5.1807E-05	7.5211E-04	7.5213E-04
21	0.7122	5.1780	7.1217E-04	52.7829	2.2130E-05	5.1885E-05	7.2735E-04	7.2733E-04
22	0.7510	5.8100	7.5103E-04	59.2253	2.2032E-05	5.1655E-05	7.7038E-04	7.7043E-04
23	0.8107	6.8248	8.1069E-04	69.5701	2.1943E-05	5.1446E-05	8.3483E-04	8.3497E-04
24	0.8877	8.1524	8.8766E-04	83.1031	2.1983E-05	5.1541E-05	9.1227E-04	9.1254E-04
25	0.9674	9.3841	9.6739E-04	95.6589	2.2330E-05	5.2354E-05	9.7864E-04	9.7901E-04
26	1.0311	10.7593	1.0311E-03	109.6767	2.2229E-05	5.2116E-05	1.0478E-03	1.0482E-03
27	0.9703	9.6693	9.7027E-04	98.5661	2.2064E-05	5.1730E-05	9.9337E-04	9.9376E-04
28	0.8780	7.8917	8.7800E-04	80.4457	2.2100E-05	5.1815E-05	8.9759E-04	8.9784E-04
29	0.8146	6.7428	8.1461E-04	68.7335	2.2183E-05	5.2009E-05	8.2980E-04	8.2994E-04
30	0.7325	5.4180	7.3247E-04	55.2294	2.2251E-05	5.2169E-05	7.4398E-04	7.4399E-04
31	0.7140	5.1766	7.1398E-04	52.7681	2.2190E-05	5.2025E-05	7.2725E-04	7.2723E-04



Experiment 12: Steel Circumferential 53mm

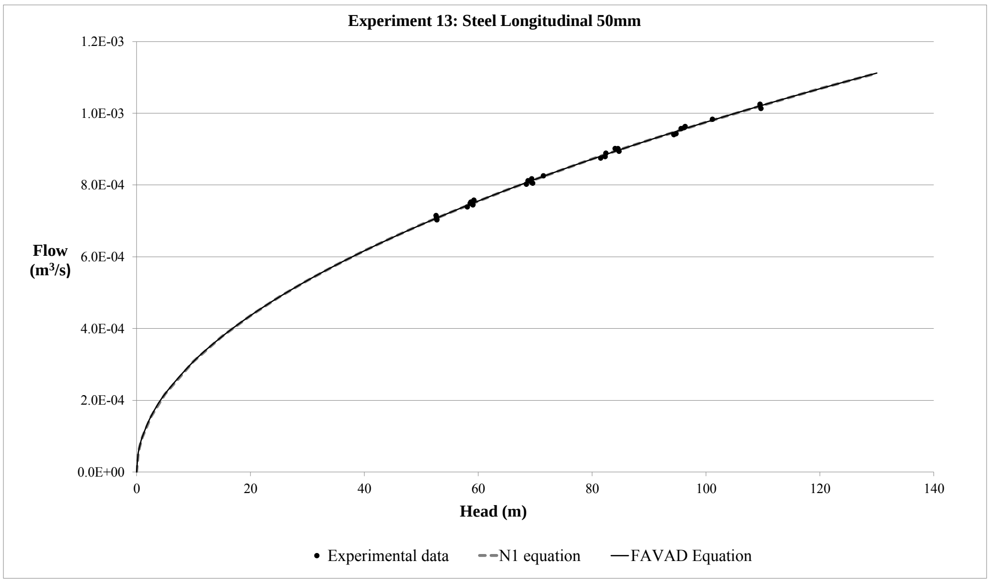




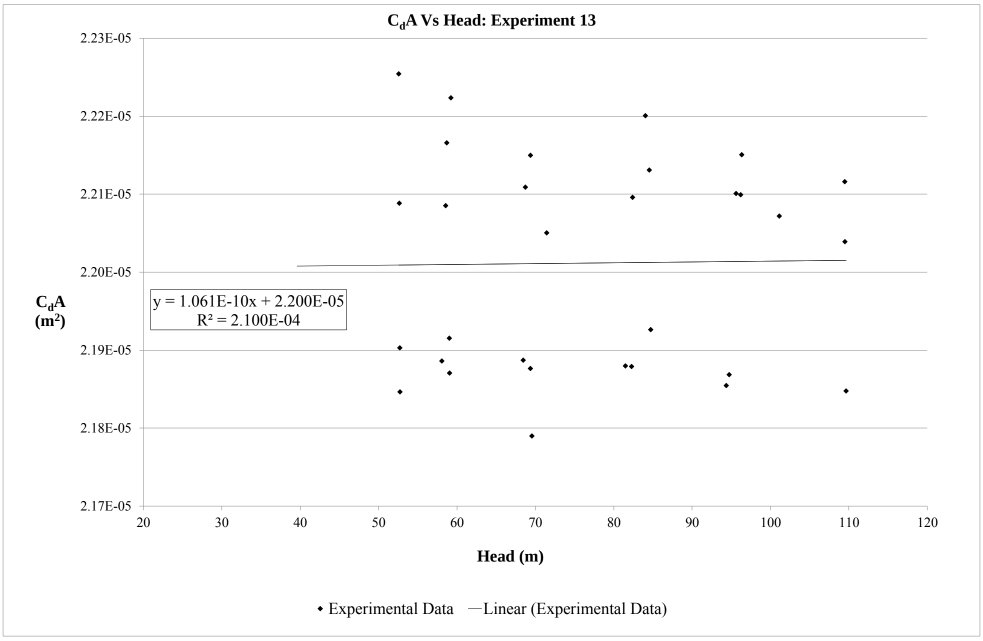
Experiment 13: Steel Longitudinal 50mm

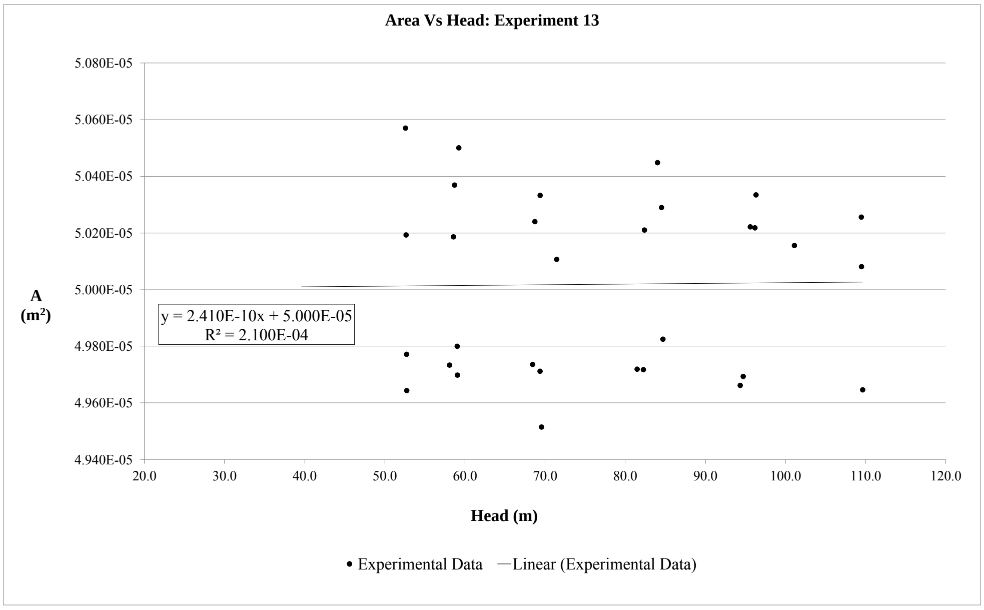
EXPERIMENTAL PARAMETERS	
1 Bar =	10.1937 m
1 l/s =	0.0010 m^3/s
g =	9.81 m/s^2
A_0 =	5.000E-05 m^2
N1 PARAMETERS	
C =	9.740E-05
N1 =	0.5002
R^2 =	0.99750
SSE =	4.538E-05
FAVAD PARAMETERS	
C_dA_0 =	2.200E-05 m^2
C_d =	0.4401
m =	2.410E-10
R^2 =	0.99750
SSE =	4.538E-05

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
1	0.7148	5.1586	7.1481E-04	52.5853	2.2254E-05	5.0570E-05	7.0695E-04	7.0694E-04
2	0.7576	5.8110	7.5762E-04	59.2358	2.2223E-05	5.0500E-05	7.5035E-04	7.5034E-04
3	0.8173	6.8069	8.1725E-04	69.3873	2.2150E-05	5.0332E-05	8.1213E-04	8.1213E-04
4	0.9015	8.2448	9.0151E-04	84.0451	2.2201E-05	5.0448E-05	8.9384E-04	8.9386E-04
5	0.9630	9.4503	9.6299E-04	96.3338	2.2150E-05	5.0334E-05	9.5699E-04	9.5704E-04
6	1.0250	10.7400	1.0250E-03	109.4801	2.2116E-05	5.0256E-05	1.0202E-03	1.0203E-03
7	0.9832	9.9207	9.8316E-04	101.1283	2.2072E-05	5.0156E-05	9.8052E-04	9.8059E-04
8	0.9013	8.2936	9.0133E-04	84.5420	2.2131E-05	5.0290E-05	8.9648E-04	8.9651E-04
9	0.8256	7.0097	8.2562E-04	71.4542	2.2050E-05	5.0107E-05	8.2414E-04	8.2414E-04
10	0.7523	5.7593	7.5228E-04	58.7086	2.2166E-05	5.0369E-05	7.4700E-04	7.4699E-04
11	0.7100	5.1662	7.1001E-04	52.6627	2.2088E-05	5.0193E-05	7.0747E-04	7.0746E-04
12	0.7487	5.7462	7.4870E-04	58.5750	2.2085E-05	5.0186E-05	7.4615E-04	7.4614E-04
13	0.8119	6.7434	8.1194E-04	68.7406	2.2109E-05	5.0240E-05	8.0833E-04	8.0833E-04
14	0.8885	8.0848	8.8851E-04	82.4141	2.2096E-05	5.0210E-05	8.8512E-04	8.8514E-04
15	0.9572	9.3800	9.5724E-04	95.6167	2.2101E-05	5.0221E-05	9.5342E-04	9.5347E-04
16	1.0215	10.7421	1.0215E-03	109.5012	2.2039E-05	5.0081E-05	1.0203E-03	1.0204E-03
17	0.9601	9.4372	9.6009E-04	96.2002	2.2099E-05	5.0218E-05	9.5632E-04	9.5638E-04
18	0.8939	8.3110	8.9394E-04	84.7200	2.1926E-05	4.9825E-05	8.9742E-04	8.9745E-04
19	0.8071	6.8062	8.0713E-04	69.3803	2.1876E-05	4.9711E-05	8.1209E-04	8.1209E-04
20	0.7388	5.6979	7.3882E-04	58.0829	2.1886E-05	4.9733E-05	7.4301E-04	7.4299E-04
21	0.7045	5.1724	7.0447E-04	52.7259	2.1903E-05	4.9771E-05	7.0790E-04	7.0788E-04
22	0.7445	5.7945	7.4453E-04	59.0671	2.1870E-05	4.9698E-05	7.4928E-04	7.4927E-04
23	0.8021	6.7159	8.0214E-04	68.4593	2.1887E-05	4.9735E-05	8.0668E-04	8.0668E-04
24	0.8749	7.9952	8.7492E-04	81.5002	2.1880E-05	4.9719E-05	8.8020E-04	8.8022E-04
25	0.9403	9.2566	9.4033E-04	94.3583	2.1854E-05	4.9661E-05	9.4712E-04	9.4717E-04
26	1.0133	10.7566	1.0133E-03	109.6488	2.1848E-05	4.9646E-05	1.0210E-03	1.0211E-03
27	0.9428	9.2938	9.4282E-04	94.7380	2.1868E-05	4.9693E-05	9.4902E-04	9.4907E-04
28	0.8791	8.0717	8.7907E-04	82.2806	2.1879E-05	4.9717E-05	8.8440E-04	8.8442E-04
29	0.8050	6.8241	8.0499E-04	69.5631	2.1790E-05	4.9515E-05	8.1316E-04	8.1316E-04
30	0.7459	5.7917	7.4587E-04	59.0390	2.1915E-05	4.9800E-05	7.4910E-04	7.4909E-04
31	0.7027	5.1738	7.0275E-04	52.7400	2.1846E-05	4.9643E-05	7.0799E-04	7.0798E-04



Experiment 13: Steel Longitudinal 50mm

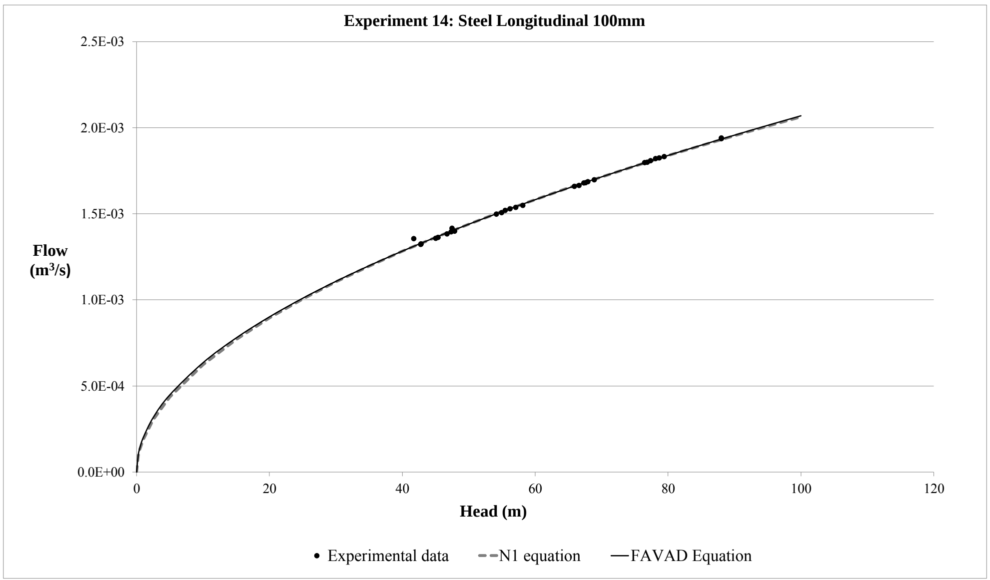




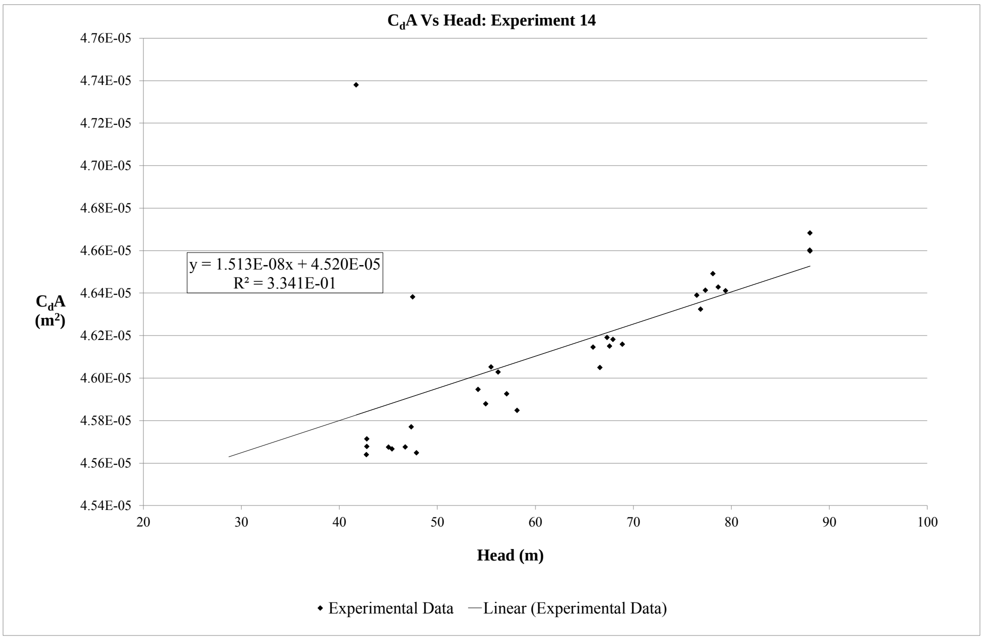
Experiment 14: Steel Longitudinal 100mm

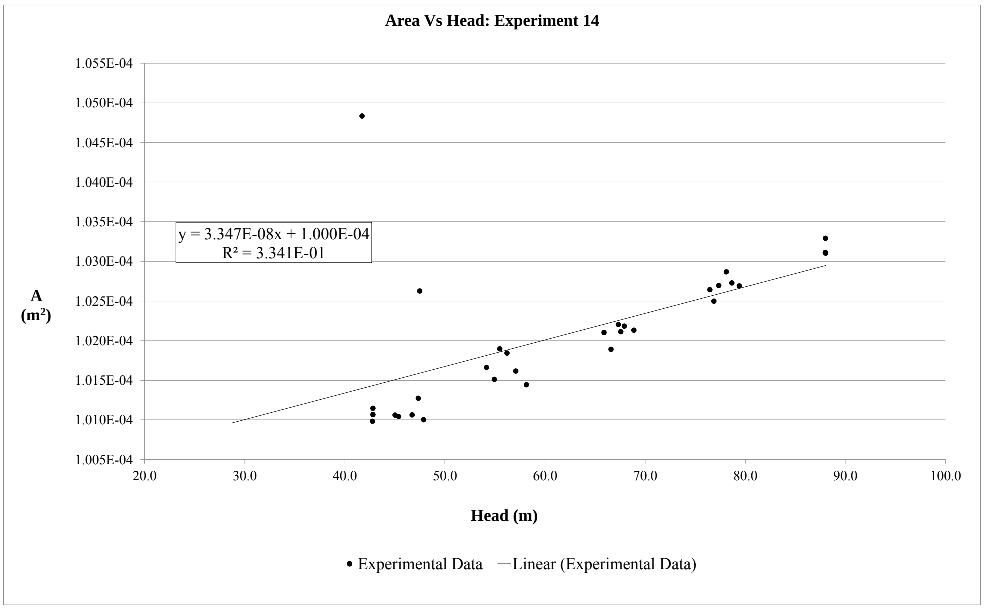
EXPERIMENTAL PARAMETERS	
1 Bar =	10.1937 m
1 l/s =	0.0010 m^3/s
g =	9.81 m/s^2
A_0 =	1.000E-04 m^2
N1 PARAMETERS	
C =	1.888E-04
N1 =	0.5193
R^2 =	0.99771
SSE =	1.608E-04
FAVAD PARAMETERS	
C_dA_0 =	4.520E-05 m^2
C_d =	0.4520
m =	3.347E-08
R^2 =	0.99785
SSE =	1.608E-04

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
1	1.3555	4.0924	1.3555E-03	41.7168	4.7380E-05	1.0483E-04	1.3105E-03	1.3111E-03
2	1.4157	4.6579	1.4157E-03	47.4815	4.6382E-05	1.0263E-04	1.4016E-03	1.4014E-03
3	1.5485	5.7036	1.5485E-03	58.1404	4.5848E-05	1.0144E-04	1.5570E-03	1.5562E-03
4	1.6970	6.7577	1.6970E-03	68.8858	4.6159E-05	1.0213E-04	1.7004E-03	1.6999E-03
5	1.8320	7.7907	1.8320E-03	79.4160	4.6411E-05	1.0269E-04	1.8307E-03	1.8314E-03
6	1.9365	8.6336	1.9365E-03	88.0079	4.6602E-05	1.0311E-04	1.9310E-03	1.9334E-03
7	1.7969	7.5021	1.7969E-03	76.4737	4.6390E-05	1.0264E-04	1.7952E-03	1.7955E-03
8	1.6592	6.4641	1.6592E-03	65.8934	4.6146E-05	1.0210E-04	1.6616E-03	1.6609E-03
9	1.4978	5.3131	1.4978E-03	54.1601	4.5947E-05	1.0166E-04	1.5007E-03	1.5000E-03
10	1.3575	4.4166	1.3575E-03	45.0209	4.5675E-05	1.0106E-04	1.3634E-03	1.3635E-03
11	1.3219	4.1948	1.3219E-03	42.7608	4.5640E-05	1.0098E-04	1.3274E-03	1.3278E-03
12	1.3950	4.6443	1.3950E-03	47.3424	4.5770E-05	1.0127E-04	1.3995E-03	1.3993E-03
13	1.5063	5.3896	1.5063E-03	54.9402	4.5879E-05	1.0151E-04	1.5119E-03	1.5111E-03
14	1.6645	6.5329	1.6645E-03	66.5939	4.6050E-05	1.0189E-04	1.6707E-03	1.6701E-03
15	1.7990	7.5407	1.7990E-03	76.8676	4.6324E-05	1.0250E-04	1.8000E-03	1.8003E-03
16	1.9366	8.6364	1.9366E-03	88.0370	4.6598E-05	1.0310E-04	1.9313E-03	1.9337E-03
17	1.8201	7.6636	1.8201E-03	78.1200	4.6491E-05	1.0287E-04	1.8151E-03	1.8157E-03
18	1.6788	6.6047	1.6788E-03	67.3259	4.6191E-05	1.0220E-04	1.6803E-03	1.6796E-03
19	1.5285	5.5138	1.5285E-03	56.2058	4.6028E-05	1.0184E-04	1.5299E-03	1.5291E-03
20	1.3626	4.4519	1.3626E-03	45.3808	4.5666E-05	1.0104E-04	1.3691E-03	1.3691E-03
21	1.3248	4.1993	1.3248E-03	42.8067	4.5713E-05	1.0115E-04	1.3282E-03	1.3286E-03
22	1.3990	4.6966	1.3990E-03	47.8751	4.5648E-05	1.0100E-04	1.4076E-03	1.4074E-03
23	1.5369	5.5993	1.5369E-03	57.0776	4.5926E-05	1.0161E-04	1.5422E-03	1.5413E-03
24	1.6804	6.6290	1.6804E-03	67.5736	4.6150E-05	1.0211E-04	1.6835E-03	1.6829E-03
25	1.8083	7.5893	1.8083E-03	77.3627	4.6413E-05	1.0269E-04	1.8060E-03	1.8064E-03
26	1.9400	8.6352	1.9400E-03	88.0242	4.6683E-05	1.0329E-04	1.9312E-03	1.9336E-03
27	1.8240	7.7172	1.8240E-03	78.6671	4.6428E-05	1.0273E-04	1.8217E-03	1.8223E-03
28	1.6859	6.6634	1.6859E-03	67.9251	4.6182E-05	1.0218E-04	1.6880E-03	1.6874E-03
29	1.5194	5.4428	1.5194E-03	55.4817	4.6053E-05	1.0190E-04	1.5196E-03	1.5188E-03
30	1.3830	4.5841	1.3830E-03	46.7292	4.5676E-05	1.0106E-04	1.3900E-03	1.3899E-03
31	1.3238	4.1993	1.3238E-03	42.8064	4.5678E-05	1.0107E-04	1.3282E-03	1.3286E-03



Experiment 14: Steel Longitudinal 100mm

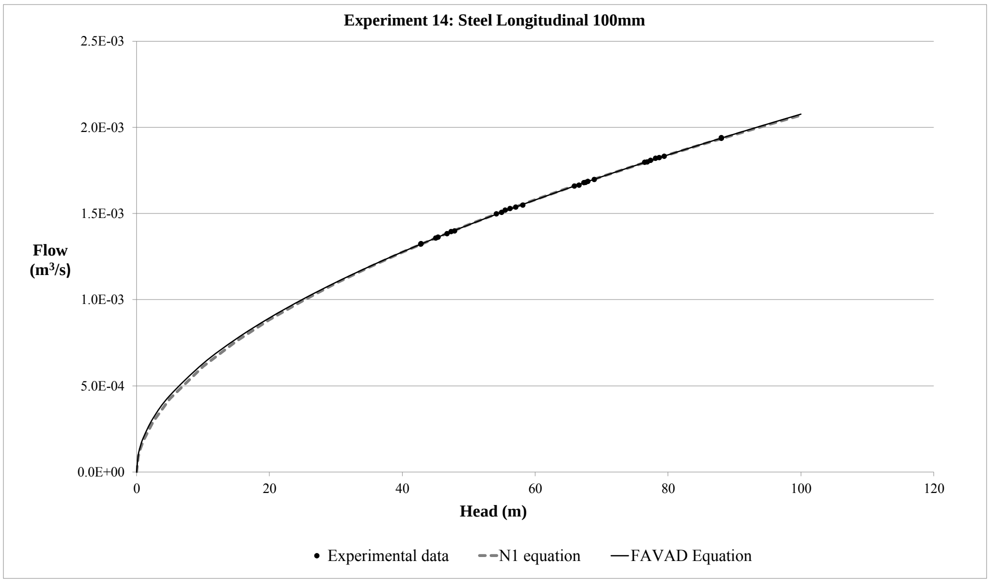




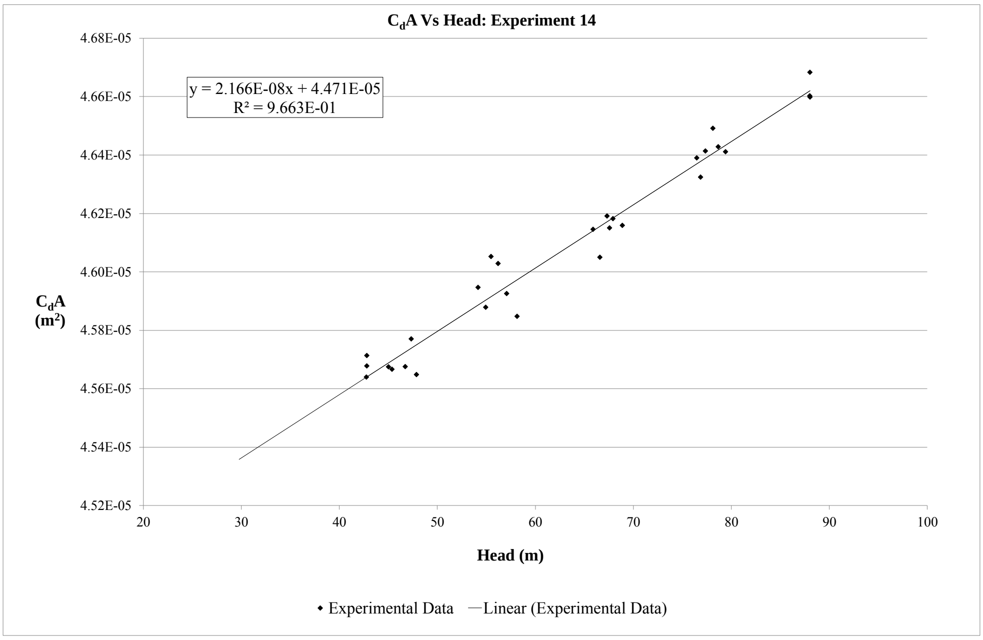
Experiment 14 (Omitted): Steel Longitudinal 100mm

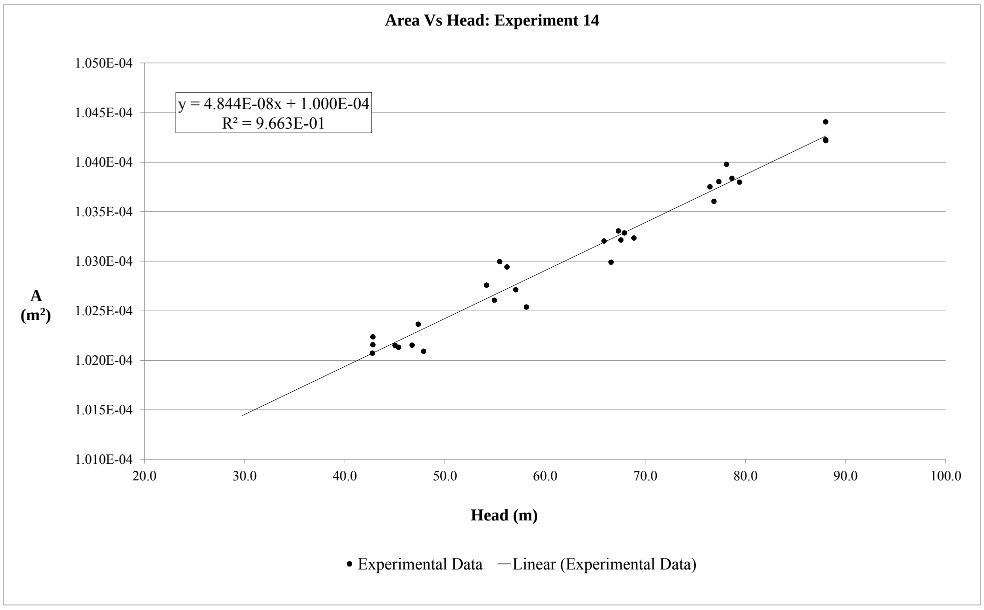
EXPERIMENTAL PARAMETERS	
1 Bar =	10.1937 m
1 l/s =	0.0010 m^3/s
g =	9.81 m/s^2
A_0 =	1.000E-04 m^2
N1 PARAMETERS	
C =	1.812E-04
N1 =	0.5289
R^2 =	0.99985
SSE =	1.531E-04
FAVAD PARAMETERS	
C_dA_0 =	4.471E-05 m^2
C_d =	0.4471
m =	4.844E-08
R^2 =	0.99990
SSE =	1.531E-04

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
3	1.5485	5.7036	1.5485E-03	58.1404	4.5848E-05	1.0254E-04	1.5538E-03	1.5527E-03
4	1.6970	6.7577	1.6970E-03	68.8858	4.6159E-05	1.0323E-04	1.6997E-03	1.6987E-03
5	1.8320	7.7907	1.8320E-03	79.4160	4.6411E-05	1.0380E-04	1.8325E-03	1.8329E-03
6	1.9365	8.6336	1.9365E-03	88.0079	4.6602E-05	1.0422E-04	1.9348E-03	1.9372E-03
7	1.7969	7.5021	1.7969E-03	76.4737	4.6390E-05	1.0375E-04	1.7963E-03	1.7961E-03
8	1.6592	6.4641	1.6592E-03	65.8934	4.6146E-05	1.0320E-04	1.6602E-03	1.6590E-03
9	1.4978	5.3131	1.4978E-03	54.1601	4.5947E-05	1.0276E-04	1.4966E-03	1.4958E-03
10	1.3575	4.4166	1.3575E-03	45.0209	4.5675E-05	1.0215E-04	1.3573E-03	1.3579E-03
11	1.3219	4.1948	1.3219E-03	42.7608	4.5640E-05	1.0207E-04	1.3208E-03	1.3219E-03
12	1.3950	4.6443	1.3950E-03	47.3424	4.5770E-05	1.0236E-04	1.3938E-03	1.3940E-03
13	1.5063	5.3896	1.5063E-03	54.9402	4.5879E-05	1.0261E-04	1.5080E-03	1.5071E-03
14	1.6645	6.5329	1.6645E-03	66.5939	4.6050E-05	1.0299E-04	1.6695E-03	1.6684E-03
15	1.7990	7.5407	1.7990E-03	76.8676	4.6324E-05	1.0360E-04	1.8012E-03	1.8011E-03
16	1.9366	8.6364	1.9366E-03	88.0370	4.6598E-05	1.0422E-04	1.9352E-03	1.9376E-03
17	1.8201	7.6636	1.8201E-03	78.1200	4.6491E-05	1.0398E-04	1.8166E-03	1.8168E-03
18	1.6788	6.6047	1.6788E-03	67.3259	4.6191E-05	1.0330E-04	1.6792E-03	1.6781E-03
19	1.5285	5.5138	1.5285E-03	56.2058	4.6028E-05	1.0294E-04	1.5263E-03	1.5253E-03
20	1.3626	4.4519	1.3626E-03	45.3808	4.5666E-05	1.0213E-04	1.3630E-03	1.3635E-03
21	1.3248	4.1993	1.3248E-03	42.8067	4.5713E-05	1.0224E-04	1.3215E-03	1.3227E-03
22	1.3990	4.6966	1.3990E-03	47.8751	4.5648E-05	1.0209E-04	1.4021E-03	1.4022E-03
23	1.5369	5.5993	1.5369E-03	57.0776	4.5926E-05	1.0271E-04	1.5388E-03	1.5377E-03
24	1.6804	6.6290	1.6804E-03	67.5736	4.6150E-05	1.0321E-04	1.6825E-03	1.6814E-03
25	1.8083	7.5893	1.8083E-03	77.3627	4.6413E-05	1.0380E-04	1.8073E-03	1.8073E-03
26	1.9400	8.6352	1.9400E-03	88.0242	4.6683E-05	1.0441E-04	1.9350E-03	1.9374E-03
27	1.8240	7.7172	1.8240E-03	78.6671	4.6428E-05	1.0384E-04	1.8233E-03	1.8236E-03
28	1.6859	6.6634	1.6859E-03	67.9251	4.6182E-05	1.0328E-04	1.6871E-03	1.6860E-03
29	1.5194	5.4428	1.5194E-03	55.4817	4.6053E-05	1.0300E-04	1.5158E-03	1.5149E-03
30	1.3830	4.5841	1.3830E-03	46.7292	4.5676E-05	1.0215E-04	1.3843E-03	1.3845E-03
31	1.3238	4.1993	1.3238E-03	42.8064	4.5678E-05	1.0216E-04	1.3215E-03	1.3227E-03



Experiment 14 (Omitted): Steel Longitudinal 100mm

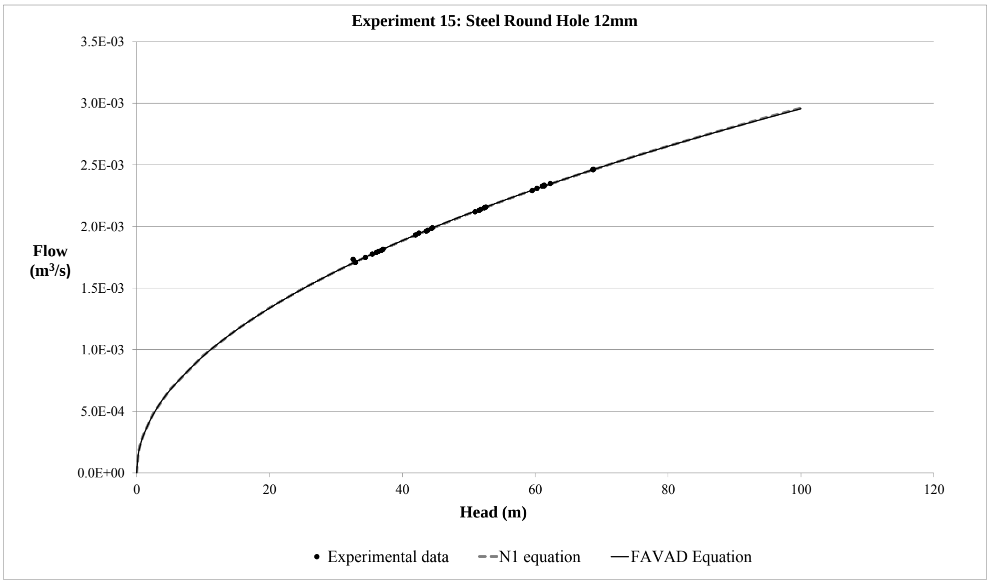




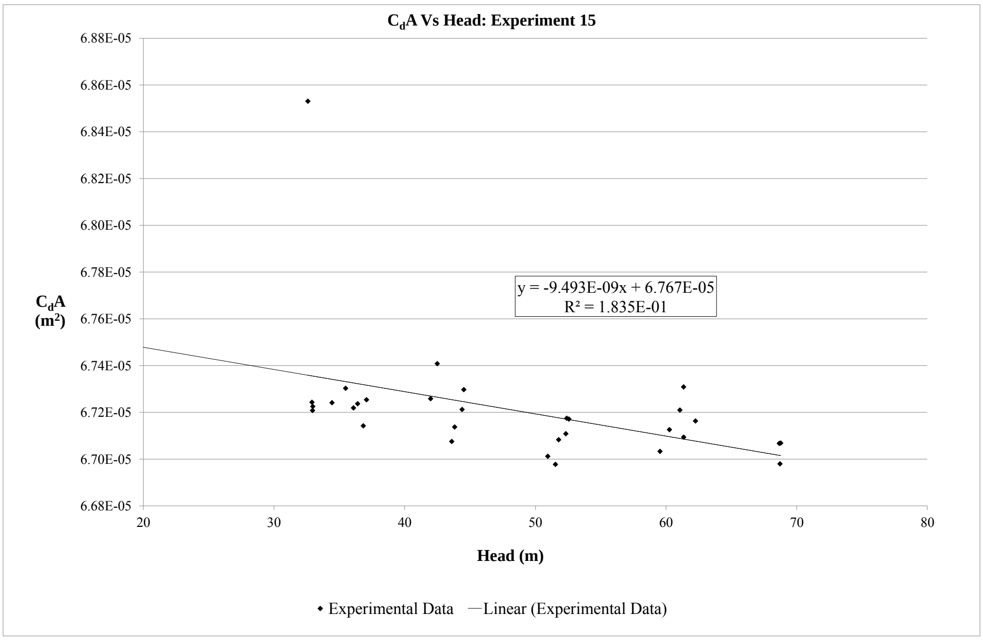
Experiment 15: Steel Round Hole 12mm

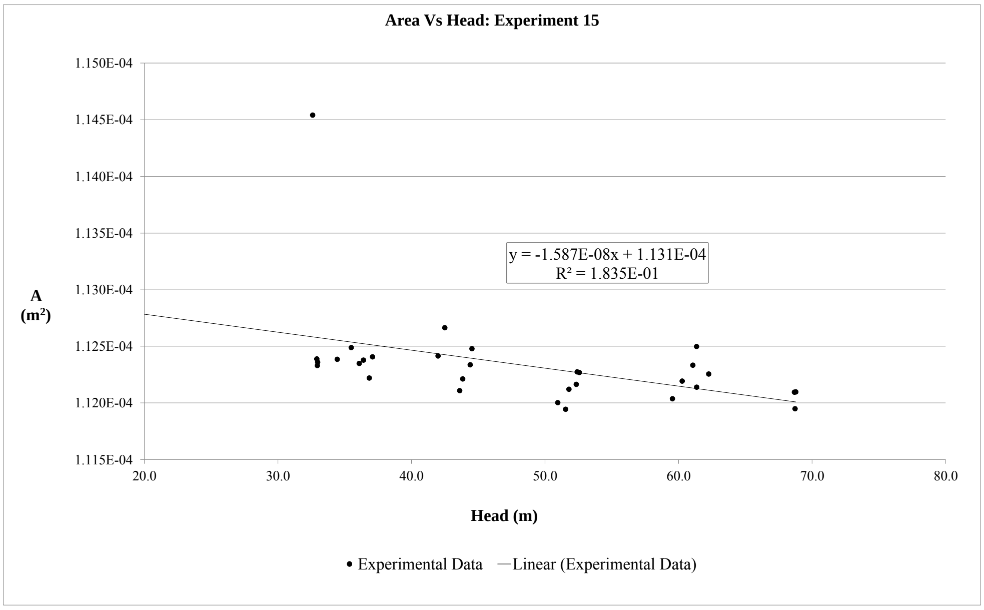
EXPERIMENTAL PARAMETERS	
1 Bar =	10.1937 m
1 l/s =	0.0010 m^3/s
g =	9.81 m/s^2
A_0 =	1.131E-04 m^2
N1 PARAMETERS	
C =	3.059E-04
N1 =	0.4929
R^2 =	0.99939
SSE =	2.643E-04
FAVAD PARAMETERS	
C_dA_0 =	6.767E-05 m^2
C_d =	0.5983
m =	-1.587E-08
R^2 =	0.99937
SSE =	2.643E-04

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
1	1.7331	3.1979	1.7331E-03	32.5987	6.8530E-05	1.1454E-04	1.7041E-03	1.7035E-03
2	1.8141	3.6379	1.8141E-03	37.0832	6.7254E-05	1.1241E-04	1.8159E-03	1.8158E-03
3	1.9837	4.3552	1.9837E-03	44.3952	6.7212E-05	1.1234E-04	1.9843E-03	1.9847E-03
4	2.1505	5.1345	2.1505E-03	52.3393	6.7109E-05	1.1216E-04	2.1521E-03	2.1525E-03
5	2.3474	6.1079	2.3474E-03	62.2615	6.7163E-05	1.1225E-04	2.3443E-03	2.3444E-03
6	2.4619	6.7372	2.4619E-03	68.6773	6.7067E-05	1.1209E-04	2.4604E-03	2.4600E-03
7	2.3352	6.0186	2.3352E-03	61.3514	6.7309E-05	1.1250E-04	2.3274E-03	2.3275E-03
8	2.1384	5.0807	2.1384E-03	51.7912	6.7083E-05	1.1212E-04	2.1409E-03	2.1414E-03
9	1.9305	4.1193	1.9305E-03	41.9907	6.7259E-05	1.1241E-04	1.9306E-03	1.9309E-03
10	1.7759	3.4814	1.7759E-03	35.4881	6.7303E-05	1.1249E-04	1.7770E-03	1.7767E-03
11	1.7086	3.2283	1.7086E-03	32.9080	6.7243E-05	1.1239E-04	1.7121E-03	1.7115E-03
12	1.7969	3.5710	1.7969E-03	36.4020	6.7237E-05	1.1238E-04	1.7994E-03	1.7992E-03
13	1.9620	4.2779	1.9620E-03	43.6079	6.7075E-05	1.1211E-04	1.9669E-03	1.9672E-03
14	2.1300	5.0566	2.1300E-03	51.5449	6.6977E-05	1.1194E-04	2.1359E-03	2.1364E-03
15	2.2912	5.8414	2.2912E-03	59.5452	6.7033E-05	1.1204E-04	2.2933E-03	2.2936E-03
16	2.4596	6.7421	2.4596E-03	68.7265	6.6980E-05	1.1195E-04	2.4613E-03	2.4609E-03
17	2.3265	5.9910	2.3265E-03	61.0707	6.7210E-05	1.1233E-04	2.3221E-03	2.3223E-03
18	2.1573	5.1572	2.1573E-03	52.5713	6.7171E-05	1.1227E-04	2.1568E-03	2.1572E-03
19	1.9891	4.3683	1.9891E-03	44.5288	6.7297E-05	1.1248E-04	1.9873E-03	1.9876E-03
20	1.7886	3.5400	1.7886E-03	36.0856	6.7219E-05	1.1235E-04	1.7916E-03	1.7914E-03
21	1.7088	3.2324	1.7088E-03	32.9496	6.7208E-05	1.1233E-04	1.7131E-03	1.7126E-03
22	1.8051	3.6138	1.8051E-03	36.8379	6.7142E-05	1.1222E-04	1.8100E-03	1.8098E-03
23	1.9689	4.3000	1.9689E-03	43.8328	6.7137E-05	1.1221E-04	1.9719E-03	1.9722E-03
24	2.1541	5.1414	2.1541E-03	52.4096	6.7175E-05	1.1227E-04	2.1535E-03	2.1540E-03
25	2.3279	6.0193	2.3279E-03	61.3589	6.7094E-05	1.1214E-04	2.3275E-03	2.3277E-03
26	2.4638	6.7476	2.4638E-03	68.7827	6.7069E-05	1.1210E-04	2.4623E-03	2.4619E-03
27	2.3083	5.9124	2.3083E-03	60.2693	6.7126E-05	1.1219E-04	2.3070E-03	2.3073E-03
28	2.1188	4.9986	2.1188E-03	50.9543	6.7012E-05	1.1200E-04	2.1238E-03	2.1243E-03
29	1.9464	4.1690	1.9464E-03	42.4971	6.7408E-05	1.1266E-04	1.9421E-03	1.9423E-03
30	1.7479	3.3787	1.7479E-03	34.4410	6.7241E-05	1.1239E-04	1.7509E-03	1.7505E-03
31	1.7099	3.2347	1.7099E-03	32.9732	6.7225E-05	1.1236E-04	1.7137E-03	1.7132E-03



Experiment 15: Steel Round Hole 12mm

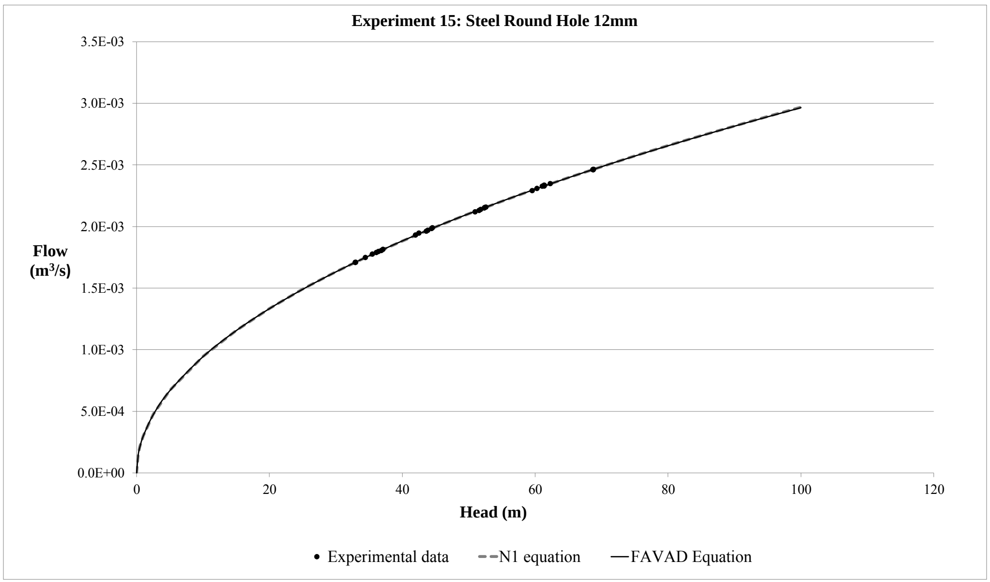




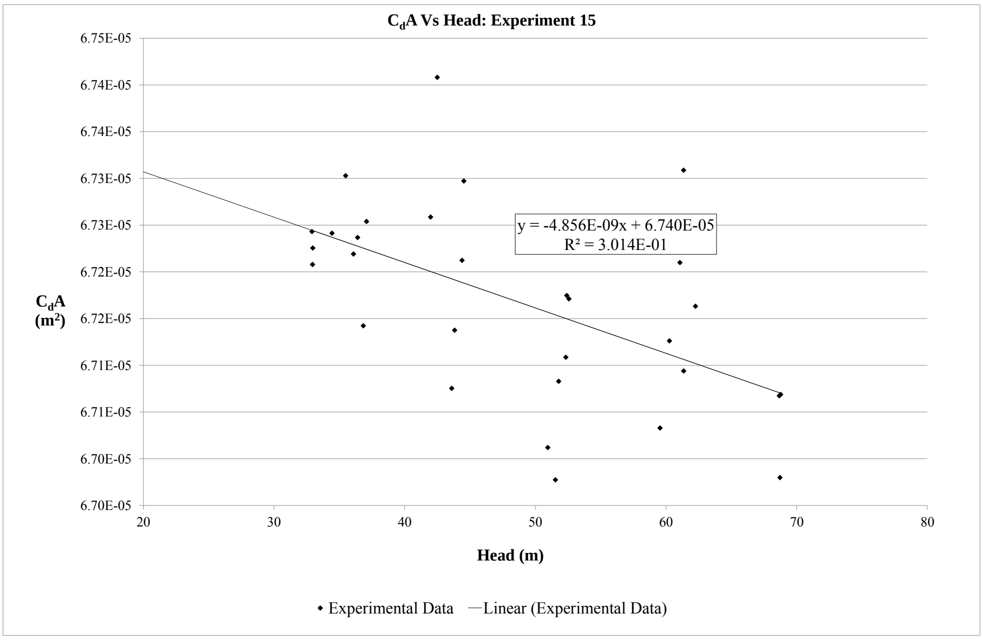
Experiment 15 (Omitted): Steel Round Hole 12mm

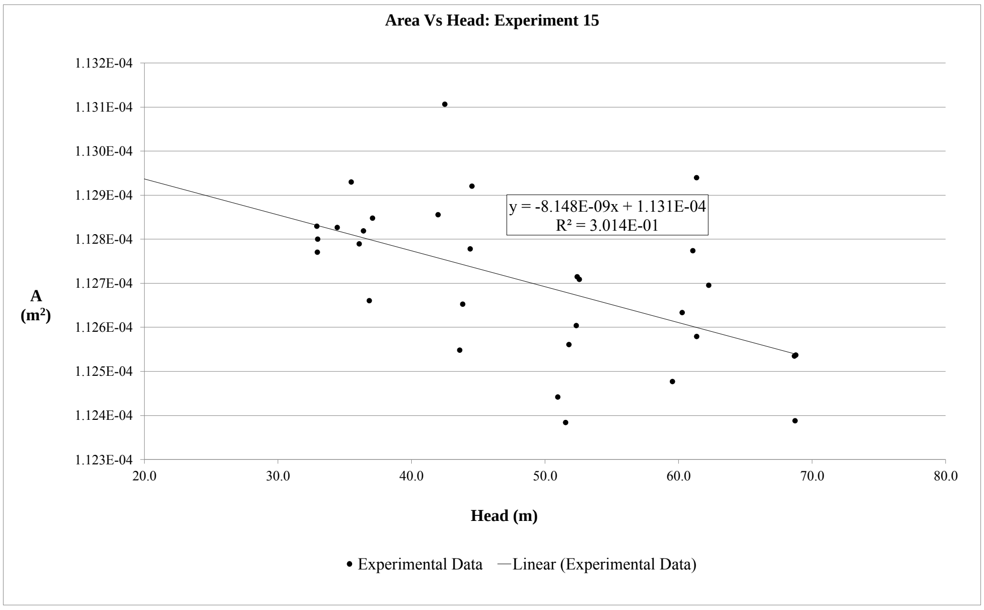
EXPERIMENTAL PARAMETERS		
1 Bar =	10.1937	m
1 l/s =	0.0010	m^3/s
g =	9.81	m/s^2
A_0 =	1.131E-04	m^2
N1 PARAMETERS		
C =	3.015E-04	
N1 =	0.4965	
R^2 =	0.99988	
SSE =	2.583E-04	
FAVAD PARAMETERS		
C_dA_0 =	6.740E-05	m^2
C_d =	0.5960	
m =	-8.148E-09	
R^2 =	0.99988	
SSE =	2.583E-04	

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
2	1.8141	3.6379	1.8141E-03	37.0832	6.7254E-05	1.1285E-04	1.8133E-03	1.8133E-03
3	1.9837	4.3552	1.9837E-03	44.3952	6.7212E-05	1.1278E-04	1.9828E-03	1.9830E-03
4	2.1505	5.1345	2.1505E-03	52.3393	6.7109E-05	1.1260E-04	2.1516E-03	2.1518E-03
5	2.3474	6.1079	2.3474E-03	62.2615	6.7163E-05	1.1270E-04	2.3453E-03	2.3453E-03
6	2.4619	6.7372	2.4619E-03	68.6773	6.7067E-05	1.1253E-04	2.4624E-03	2.4620E-03
7	2.3352	6.0186	2.3352E-03	61.3514	6.7309E-05	1.1294E-04	2.3282E-03	2.3282E-03
8	2.1384	5.0807	2.1384E-03	51.7912	6.7083E-05	1.1256E-04	2.1404E-03	2.1406E-03
9	1.9305	4.1193	1.9305E-03	41.9907	6.7259E-05	1.1286E-04	1.9287E-03	1.9288E-03
10	1.7759	3.4814	1.7759E-03	35.4881	6.7303E-05	1.1293E-04	1.7741E-03	1.7741E-03
11	1.7086	3.2283	1.7086E-03	32.9080	6.7243E-05	1.1283E-04	1.7089E-03	1.7087E-03
12	1.7969	3.5710	1.7969E-03	36.4020	6.7237E-05	1.1282E-04	1.7967E-03	1.7966E-03
13	1.9620	4.2779	1.9620E-03	43.6079	6.7075E-05	1.1255E-04	1.9652E-03	1.9654E-03
14	2.1300	5.0566	2.1300E-03	51.5449	6.6977E-05	1.1238E-04	2.1354E-03	2.1356E-03
15	2.2912	5.8414	2.2912E-03	59.5452	6.7033E-05	1.1248E-04	2.2940E-03	2.2940E-03
16	2.4596	6.7421	2.4596E-03	68.7265	6.6980E-05	1.1239E-04	2.4632E-03	2.4629E-03
17	2.3265	5.9910	2.3265E-03	61.0707	6.7210E-05	1.1277E-04	2.3230E-03	2.3229E-03
18	2.1573	5.1572	2.1573E-03	52.5713	6.7171E-05	1.1271E-04	2.1564E-03	2.1566E-03
19	1.9891	4.3683	1.9891E-03	44.5288	6.7297E-05	1.1292E-04	1.9857E-03	1.9859E-03
20	1.7886	3.5400	1.7886E-03	36.0856	6.7219E-05	1.1279E-04	1.7889E-03	1.7888E-03
21	1.7088	3.2324	1.7088E-03	32.9496	6.7208E-05	1.1277E-04	1.7099E-03	1.7097E-03
22	1.8051	3.6138	1.8051E-03	36.8379	6.7142E-05	1.1266E-04	1.8073E-03	1.8073E-03
23	1.9689	4.3000	1.9689E-03	43.8328	6.7137E-05	1.1265E-04	1.9703E-03	1.9704E-03
24	2.1541	5.1414	2.1541E-03	52.4096	6.7175E-05	1.1271E-04	2.1531E-03	2.1533E-03
25	2.3279	6.0193	2.3279E-03	61.3589	6.7094E-05	1.1258E-04	2.3284E-03	2.3284E-03
26	2.4638	6.7476	2.4638E-03	68.7827	6.7069E-05	1.1254E-04	2.4642E-03	2.4639E-03
27	2.3083	5.9124	2.3083E-03	60.2693	6.7126E-05	1.1263E-04	2.3078E-03	2.3078E-03
28	2.1188	4.9986	2.1188E-03	50.9543	6.7012E-05	1.1244E-04	2.1232E-03	2.1234E-03
29	1.9464	4.1690	1.9464E-03	42.4971	6.7408E-05	1.1311E-04	1.9402E-03	1.9404E-03
30	1.7479	3.3787	1.7479E-03	34.4410	6.7241E-05	1.1283E-04	1.7479E-03	1.7478E-03
31	1.7099	3.2347	1.7099E-03	32.9732	6.7225E-05	1.1280E-04	1.7106E-03	1.7103E-03



Experiment 15 (Omitted): Steel Round Hole 12mm

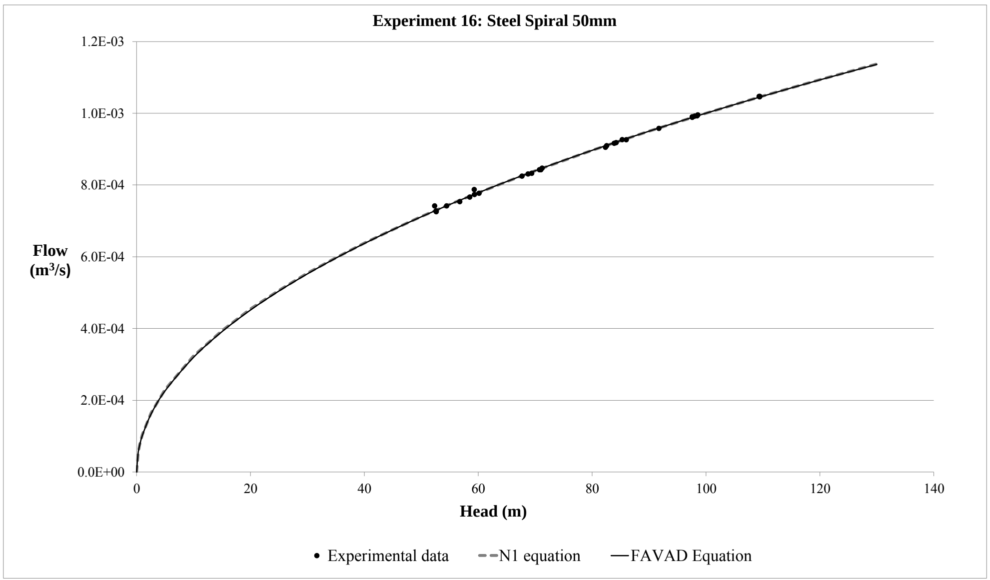




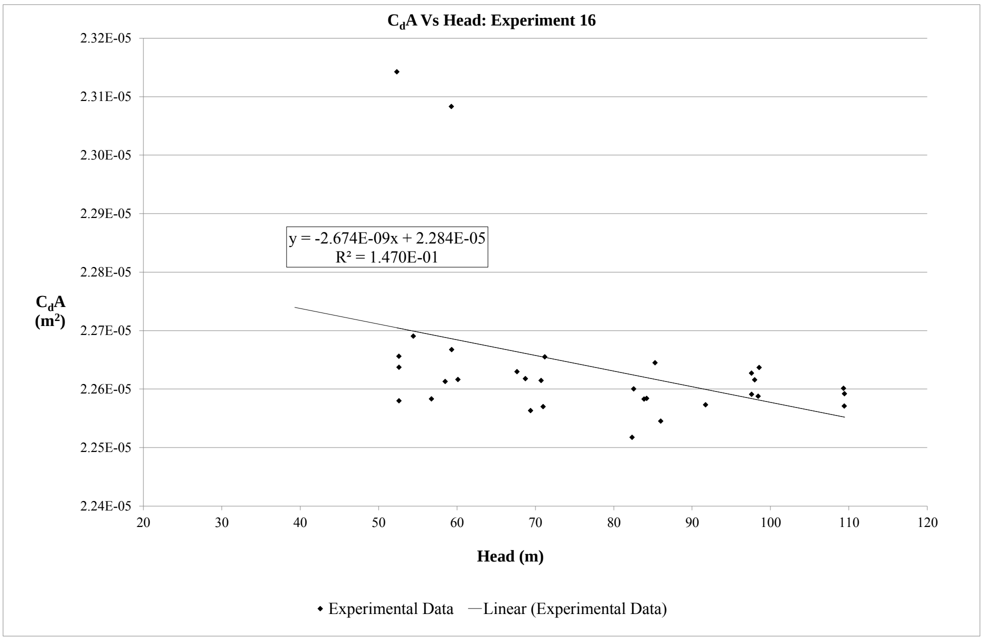
Experiment 16: Steel Spiral 50mm

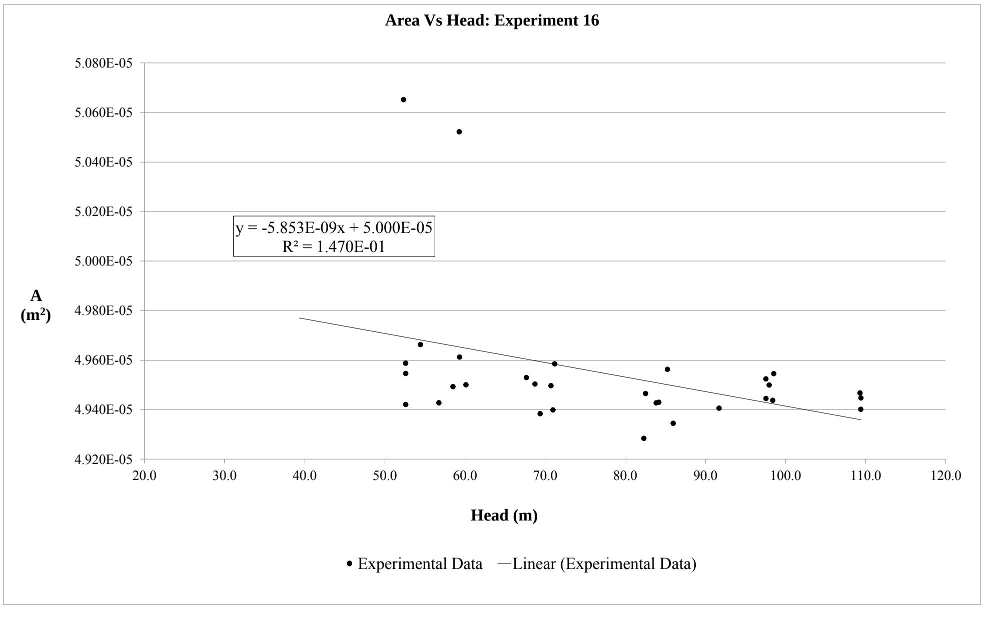
EXPERIMENTAL PARAMETERS	
1 Bar =	10.1937 m
1 l/s =	0.0010 m^3/s
g =	9.81 m/s^2
A_0 =	5.000E-05 m^2
N1 PARAMETERS	
C =	1.045E-04
N1 =	0.4905
R^2 =	0.99853
SSE =	4.804E-05
FAVAD PARAMETERS	
C_dA_0 =	2.284E-05 m^2
C_d =	0.4569
m =	-5.853E-09
R^2 =	0.99848
SSE =	4.805E-05

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
1	0.7416	5.1341	7.4158E-04	52.3351	2.3142E-05	5.0652E-05	7.2789E-04	7.2755E-04
2	0.7873	5.8164	7.8730E-04	59.2908	2.3083E-05	5.0522E-05	7.7383E-04	7.7376E-04
3	0.8424	6.9646	8.4236E-04	70.9951	2.2570E-05	4.9399E-05	8.4533E-04	8.4552E-04
4	0.9261	8.4366	9.2609E-04	85.9995	2.2545E-05	4.9345E-05	9.2868E-04	9.2894E-04
5	0.9954	9.6683	9.9542E-04	98.5553	2.2637E-05	4.9545E-05	9.9288E-04	9.9297E-04
6	1.0469	10.7357	1.0469E-03	109.4364	2.2592E-05	4.9447E-05	1.0452E-03	1.0450E-03
7	0.9576	8.9979	9.5758E-04	91.7213	2.2573E-05	4.9406E-05	9.5849E-04	9.5870E-04
8	0.9051	8.0779	9.0508E-04	82.3438	2.2518E-05	4.9284E-05	9.0910E-04	9.0938E-04
9	0.8306	6.7436	8.3063E-04	68.7418	2.2618E-05	4.9503E-05	8.3206E-04	8.3222E-04
10	0.7661	5.7393	7.6613E-04	58.5047	2.2613E-05	4.9493E-05	7.6878E-04	7.6868E-04
11	0.7274	5.1621	7.2736E-04	52.6205	2.2637E-05	4.9546E-05	7.2983E-04	7.2951E-04
12	0.7734	5.8207	7.7340E-04	59.3342	2.2667E-05	4.9612E-05	7.7411E-04	7.7404E-04
13	0.8325	6.8076	8.3255E-04	69.3944	2.2563E-05	4.9384E-05	8.3592E-04	8.3609E-04
14	0.9180	8.2607	9.1796E-04	84.2068	2.2584E-05	4.9429E-05	9.1913E-04	9.1941E-04
15	0.9900	9.5724	9.9005E-04	97.5781	2.2627E-05	4.9524E-05	9.8804E-04	9.8815E-04
16	1.0467	10.7241	1.0467E-03	109.3184	2.2601E-05	4.9467E-05	1.0447E-03	1.0445E-03
17	0.9926	9.6557	9.9261E-04	98.4273	2.2588E-05	4.9437E-05	9.9224E-04	9.9234E-04
18	0.9263	8.3655	9.2626E-04	85.2754	2.2645E-05	4.9563E-05	9.2484E-04	9.2510E-04
19	0.8468	6.9858	8.4682E-04	71.2111	2.2655E-05	4.9585E-05	8.4659E-04	8.4679E-04
20	0.7536	5.5674	7.5358E-04	56.7524	2.2583E-05	4.9428E-05	7.5740E-04	7.5724E-04
21	0.7255	5.1614	7.2547E-04	52.6134	2.2580E-05	4.9420E-05	7.2979E-04	7.2946E-04
22	0.7769	5.8993	7.7685E-04	60.1357	2.2616E-05	4.9500E-05	7.7922E-04	7.7917E-04
23	0.8425	6.9400	8.4253E-04	70.7441	2.2615E-05	4.9496E-05	8.4386E-04	8.4405E-04
24	0.9161	8.2283	9.1612E-04	83.8764	2.2583E-05	4.9427E-05	9.1736E-04	9.1764E-04
25	0.9885	9.5731	9.8850E-04	97.5852	2.2591E-05	4.9445E-05	9.8807E-04	9.8818E-04
26	1.0458	10.7331	1.0458E-03	109.4098	2.2571E-05	4.9401E-05	1.0451E-03	1.0449E-03
27	0.9916	9.6120	9.9159E-04	97.9817	2.2616E-05	4.9499E-05	9.9004E-04	9.9014E-04
28	0.9095	8.0979	9.0952E-04	82.5470	2.2600E-05	4.9465E-05	9.1020E-04	9.1048E-04
29	0.8246	6.6386	8.2458E-04	67.6720	2.2630E-05	4.9529E-05	8.2568E-04	8.2582E-04
30	0.7416	5.3407	7.4158E-04	54.4413	2.2690E-05	4.9662E-05	7.4211E-04	7.4186E-04
31	0.7279	5.1607	7.2787E-04	52.6062	2.2656E-05	4.9587E-05	7.2974E-04	7.2941E-04



Experiment 16: Steel Spiral 50mm

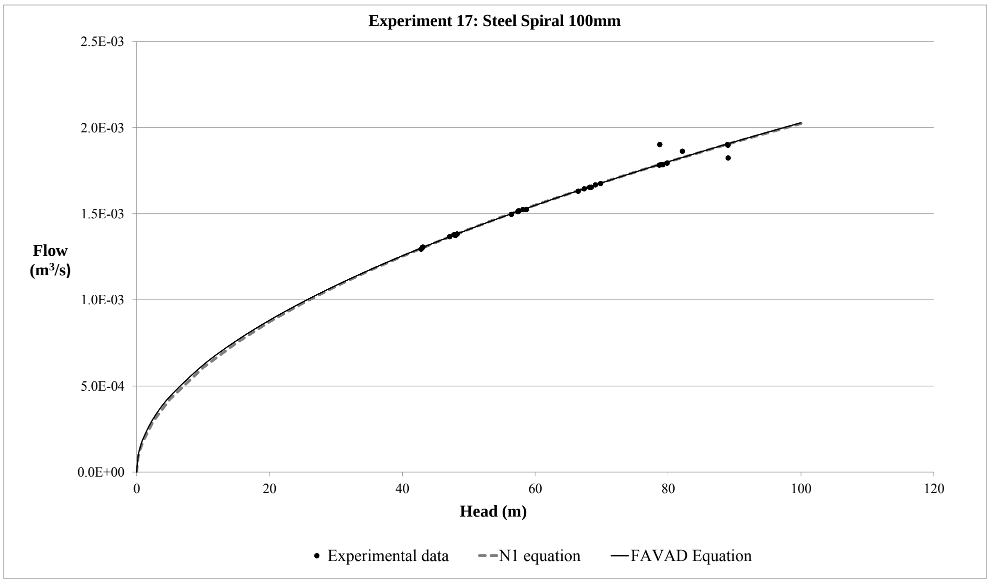




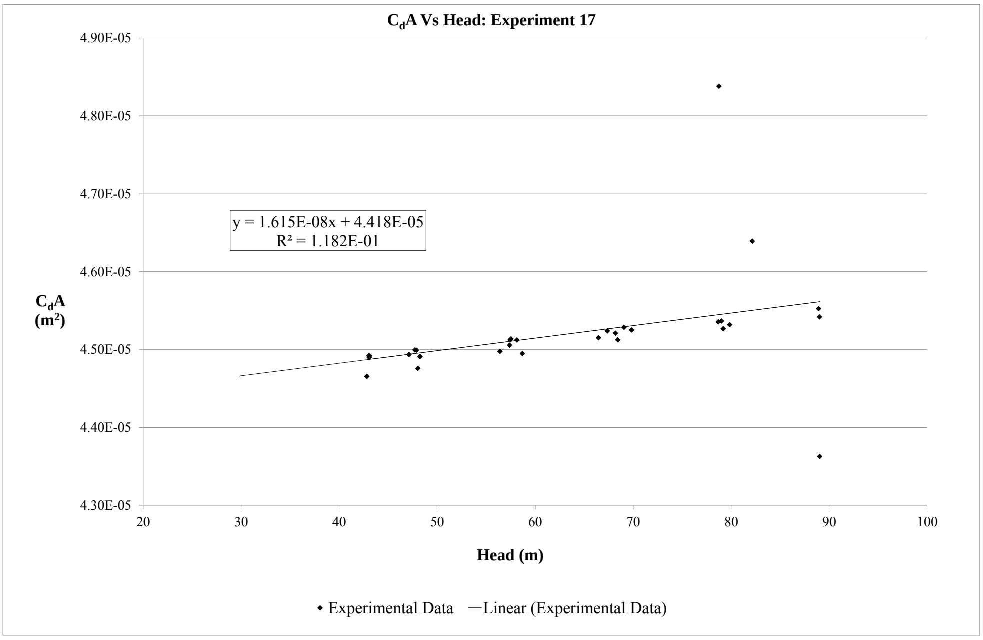
Experiment 17: Steel Spiral 105mm

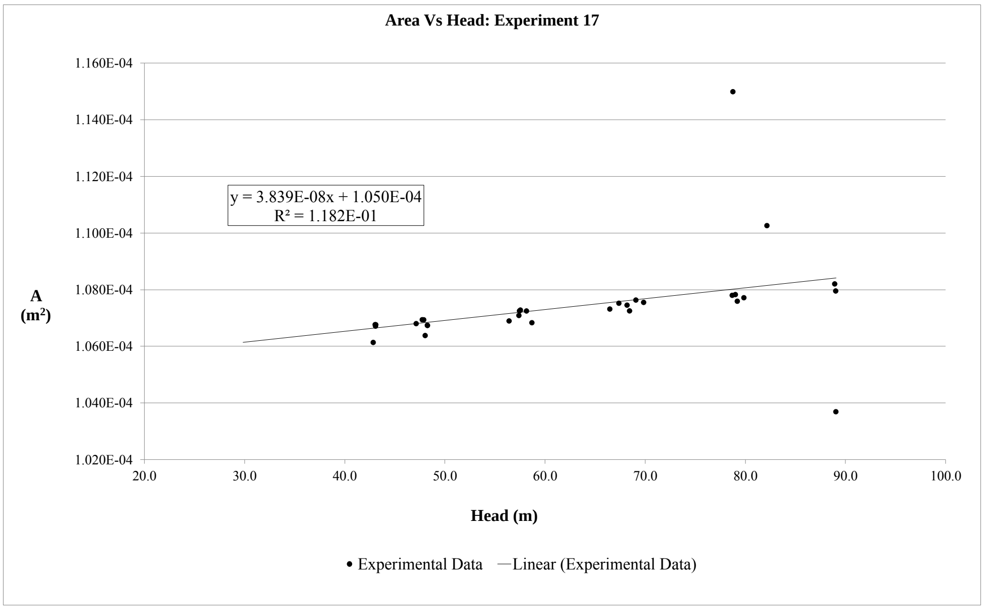
EXPERIMENTAL PARAMETERS	
1 Bar =	10.1937 m
1 l/s =	0.0010 m^3/s
g =	9.81 m/s^2
A_0 =	1.050E-04 m^2
N1 PARAMETERS	
C =	1.824E-04
N1 =	0.5226
R^2 =	0.98249
SSE =	1.575E-04
FAVAD PARAMETERS	
C_dA_0 =	4.418E-05 m^2
C_d =	0.4207
m =	3.839E-08
R^2 =	0.98230
SSE =	1.575E-04

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
1	1.2947	4.2028	1.2947E-03	42.8416	4.4655E-05	1.0613E-04	1.2996E-03	1.3009E-03
2	1.3740	4.7117	1.3740E-03	48.0298	4.4758E-05	1.0638E-04	1.3796E-03	1.3800E-03
3	1.5253	5.7578	1.5253E-03	58.6929	4.4948E-05	1.0683E-04	1.5320E-03	1.5313E-03
4	1.6535	6.7138	1.6535E-03	68.4383	4.5124E-05	1.0725E-04	1.6601E-03	1.6593E-03
5	1.7844	7.7697	1.7844E-03	79.2014	4.5267E-05	1.0759E-04	1.7918E-03	1.7919E-03
6	1.9016	8.7234	1.9016E-03	88.9240	4.5525E-05	1.0820E-04	1.9036E-03	1.9053E-03
7	1.7821	7.7193	1.7821E-03	78.6882	4.5355E-05	1.0780E-04	1.7857E-03	1.7858E-03
8	1.6670	6.7759	1.6670E-03	69.0710	4.5284E-05	1.0763E-04	1.6681E-03	1.6674E-03
9	1.5241	5.7041	1.5241E-03	58.1462	4.5122E-05	1.0724E-04	1.5246E-03	1.5239E-03
10	1.3770	4.6834	1.3770E-03	47.7416	4.4993E-05	1.0694E-04	1.3753E-03	1.3757E-03
11	1.3052	4.2214	1.3052E-03	43.0314	4.4920E-05	1.0676E-04	1.3026E-03	1.3038E-03
12	1.3819	4.7345	1.3819E-03	48.2618	4.4908E-05	1.0673E-04	1.3831E-03	1.3834E-03
13	1.5119	5.6303	1.5119E-03	57.3939	4.5056E-05	1.0709E-04	1.5142E-03	1.5136E-03
14	1.6537	6.6897	1.6537E-03	68.1922	4.5210E-05	1.0745E-04	1.6570E-03	1.6562E-03
15	1.7938	7.8338	1.7938E-03	79.8552	4.5319E-05	1.0771E-04	1.7995E-03	1.7997E-03
16	1.8982	8.7331	1.8982E-03	89.0225	4.5419E-05	1.0795E-04	1.9047E-03	1.9064E-03
17	1.7862	7.7510	1.7862E-03	79.0116	4.5366E-05	1.0782E-04	1.7896E-03	1.7896E-03
18	1.6448	6.6097	1.6448E-03	67.3767	4.5238E-05	1.0752E-04	1.6466E-03	1.6458E-03
19	1.5166	5.6448	1.5166E-03	57.5416	4.5136E-05	1.0728E-04	1.5163E-03	1.5156E-03
20	1.3664	4.6234	1.3664E-03	47.1300	4.4935E-05	1.0680E-04	1.3661E-03	1.3665E-03
21	1.3062	4.2283	1.3062E-03	43.1017	4.4918E-05	1.0676E-04	1.3037E-03	1.3049E-03
22	1.3818	4.7331	1.3818E-03	48.2477	4.4910E-05	1.0674E-04	1.3829E-03	1.3832E-03
23	1.4962	5.5338	1.4962E-03	56.4097	4.4975E-05	1.0689E-04	1.5006E-03	1.5000E-03
24	1.6305	6.5207	1.6305E-03	66.4698	4.5151E-05	1.0731E-04	1.6350E-03	1.6342E-03
25	1.9018	7.7262	1.9018E-03	78.7585	4.8380E-05	1.1499E-04	1.7866E-03	1.7866E-03
26	1.8235	8.7352	1.8235E-03	89.0436	4.3626E-05	1.0369E-04	1.9049E-03	1.9066E-03
27	1.8626	8.0600	1.8626E-03	82.1611	4.6391E-05	1.1026E-04	1.8265E-03	1.8270E-03
28	1.6751	6.8517	1.6751E-03	69.8443	4.5250E-05	1.0755E-04	1.6779E-03	1.6771E-03
29	1.5150	5.6359	1.5150E-03	57.4502	4.5124E-05	1.0725E-04	1.5150E-03	1.5144E-03
30	1.3791	4.6979	1.3791E-03	47.8892	4.4991E-05	1.0693E-04	1.3775E-03	1.3779E-03
31	1.3052	4.2255	1.3052E-03	43.0736	4.4897E-05	1.0671E-04	1.3033E-03	1.3045E-03



Experiment 17: Steel Spiral 105mm

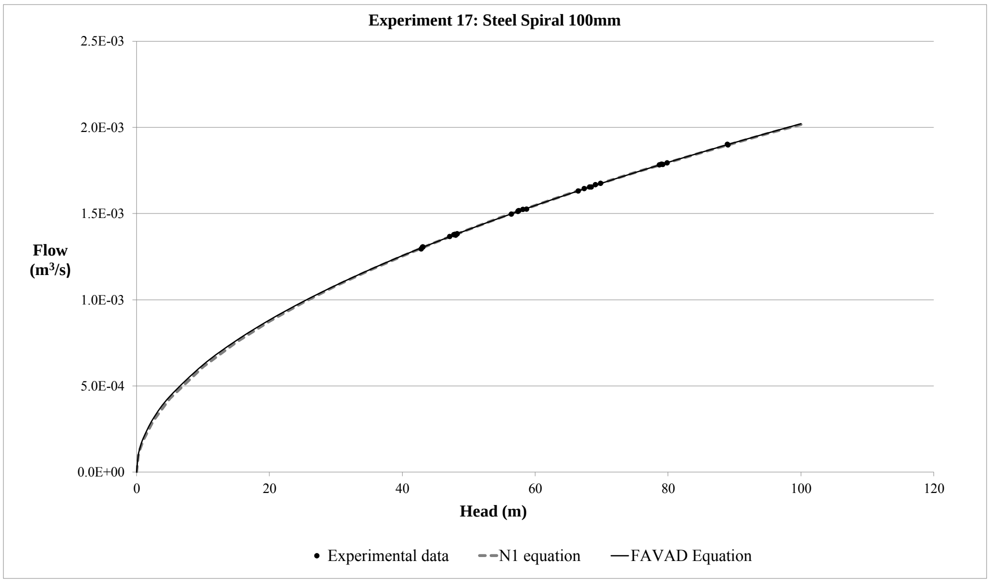




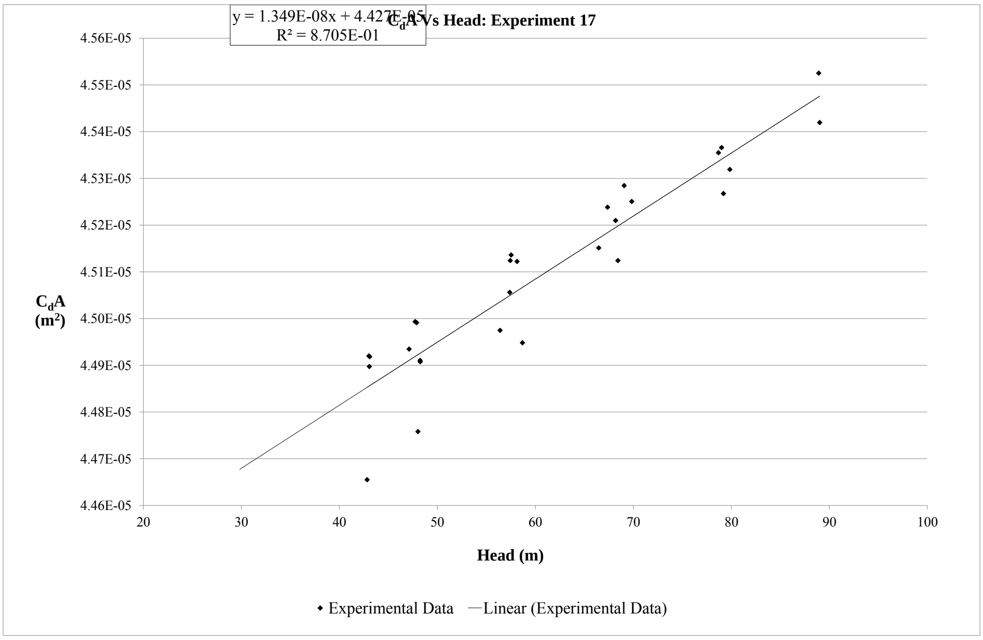
Experiment 17 (Omitted): Steel Spiral 105mm

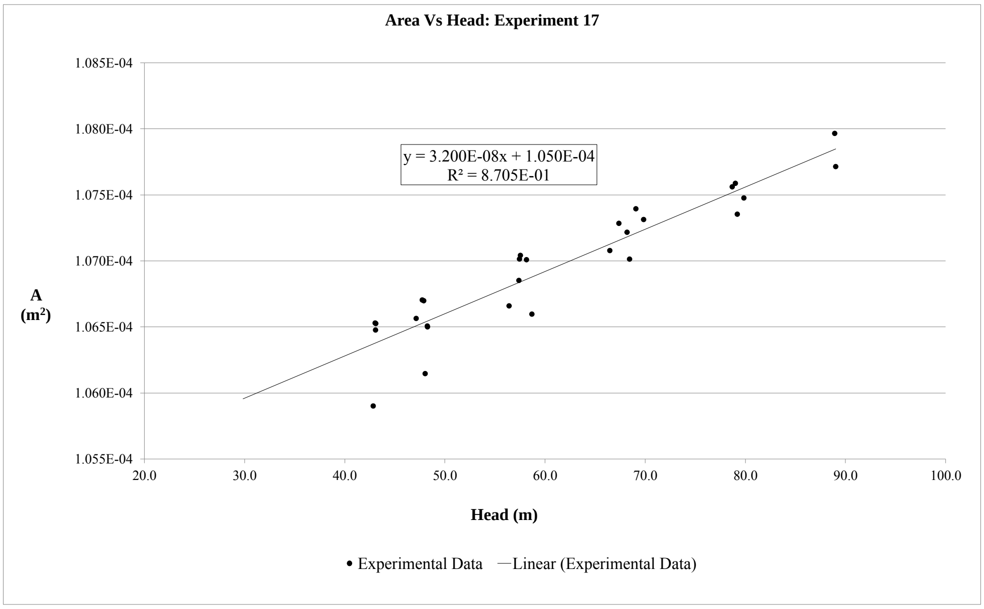
EXPERIMENTAL PARAMETERS	
1 Bar =	10.1937 m
1 l/s =	0.0010 m^3/s
g =	9.81 m/s^2
A_0 =	1.050E-04 m^2
N1 PARAMETERS	
C =	1.853E-04
N1 =	0.5184
R^2 =	0.99983
SSE =	1.367E-04
FAVAD PARAMETERS	
C_dA_0 =	4.427E-05 m^2
C_d =	0.4217
m =	3.200E-08
R^2 =	0.99983
SSE =	1.367E-04

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
1	1.2947	4.2028	1.2947E-03	42.8416	4.4655E-05	1.0590E-04	1.2996E-03	1.3004E-03
2	1.3740	4.7117	1.3740E-03	48.0298	4.4758E-05	1.0615E-04	1.3790E-03	1.3790E-03
3	1.5253	5.7578	1.5253E-03	58.6929	4.4948E-05	1.0660E-04	1.5300E-03	1.5293E-03
4	1.6535	6.7138	1.6535E-03	68.4383	4.5124E-05	1.0701E-04	1.6568E-03	1.6562E-03
5	1.7844	7.7697	1.7844E-03	79.2014	4.5267E-05	1.0735E-04	1.7872E-03	1.7874E-03
6	1.9016	8.7234	1.9016E-03	88.9240	4.5525E-05	1.0797E-04	1.8977E-03	1.8995E-03
7	1.7821	7.7193	1.7821E-03	78.6882	4.5355E-05	1.0756E-04	1.7812E-03	1.7814E-03
8	1.6670	6.7759	1.6670E-03	69.0710	4.5284E-05	1.0739E-04	1.6648E-03	1.6642E-03
9	1.5241	5.7041	1.5241E-03	58.1462	4.5122E-05	1.0701E-04	1.5226E-03	1.5219E-03
10	1.3770	4.6834	1.3770E-03	47.7416	4.4993E-05	1.0670E-04	1.3747E-03	1.3748E-03
11	1.3052	4.2214	1.3052E-03	43.0314	4.4920E-05	1.0653E-04	1.3026E-03	1.3033E-03
12	1.3819	4.7345	1.3819E-03	48.2618	4.4908E-05	1.0650E-04	1.3824E-03	1.3825E-03
13	1.5119	5.6303	1.5119E-03	57.3939	4.5056E-05	1.0685E-04	1.5124E-03	1.5117E-03
14	1.6537	6.6897	1.6537E-03	68.1922	4.5210E-05	1.0722E-04	1.6538E-03	1.6531E-03
15	1.7938	7.8338	1.7938E-03	79.8552	4.5319E-05	1.0748E-04	1.7948E-03	1.7951E-03
16	1.8982	8.7331	1.8982E-03	89.0225	4.5419E-05	1.0771E-04	1.8988E-03	1.9006E-03
17	1.7862	7.7510	1.7862E-03	79.0116	4.5366E-05	1.0759E-04	1.7850E-03	1.7852E-03
18	1.6448	6.6097	1.6448E-03	67.3767	4.5238E-05	1.0728E-04	1.6435E-03	1.6428E-03
19	1.5166	5.6448	1.5166E-03	57.5416	4.5136E-05	1.0704E-04	1.5144E-03	1.5137E-03
20	1.3664	4.6234	1.3664E-03	47.1300	4.4935E-05	1.0656E-04	1.3655E-03	1.3657E-03
21	1.3062	4.2283	1.3062E-03	43.1017	4.4918E-05	1.0653E-04	1.3037E-03	1.3044E-03
22	1.3818	4.7331	1.3818E-03	48.2477	4.4910E-05	1.0651E-04	1.3822E-03	1.3822E-03
23	1.4962	5.5338	1.4962E-03	56.4097	4.4975E-05	1.0666E-04	1.4989E-03	1.4983E-03
24	1.6305	6.5207	1.6305E-03	66.4698	4.5151E-05	1.0708E-04	1.6320E-03	1.6313E-03
28	1.6751	6.8517	1.6751E-03	69.8443	4.5250E-05	1.0731E-04	1.6744E-03	1.6739E-03
29	1.5150	5.6359	1.5150E-03	57.4502	4.5124E-05	1.0701E-04	1.5131E-03	1.5125E-03
30	1.3791	4.6979	1.3791E-03	47.8892	4.4991E-05	1.0670E-04	1.3769E-03	1.3769E-03
31	1.3052	4.2255	1.3052E-03	43.0736	4.4897E-05	1.0648E-04	1.3033E-03	1.3040E-03



Experiment 17 (Omitted): Steel Spiral 105mm

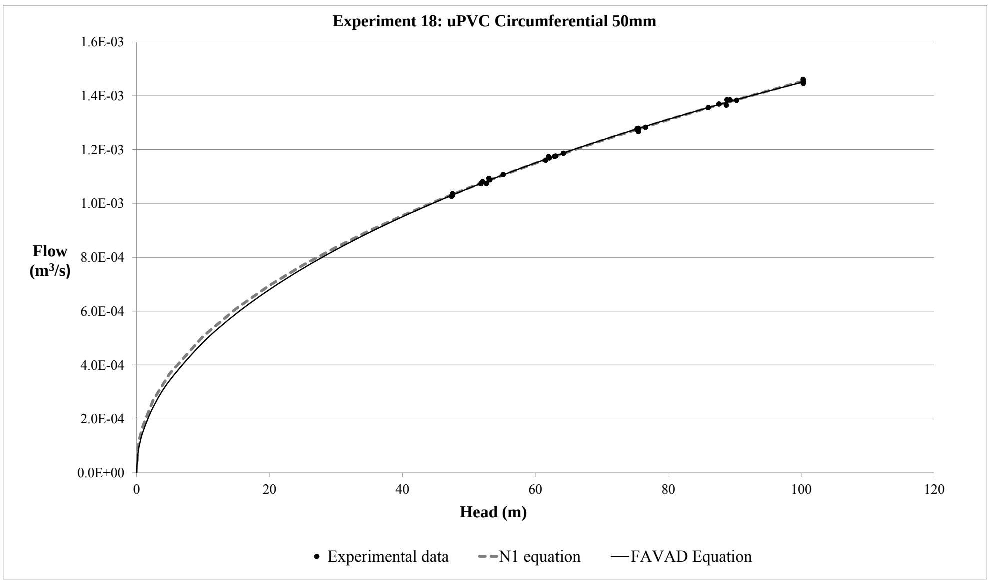




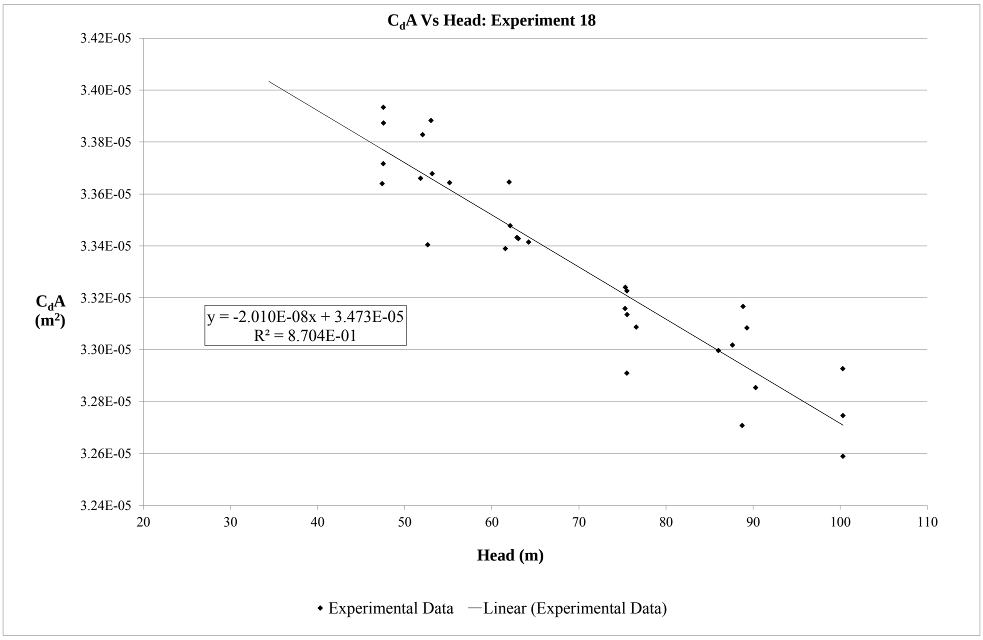
Experiment 18: uPVC Circumferential 50mm

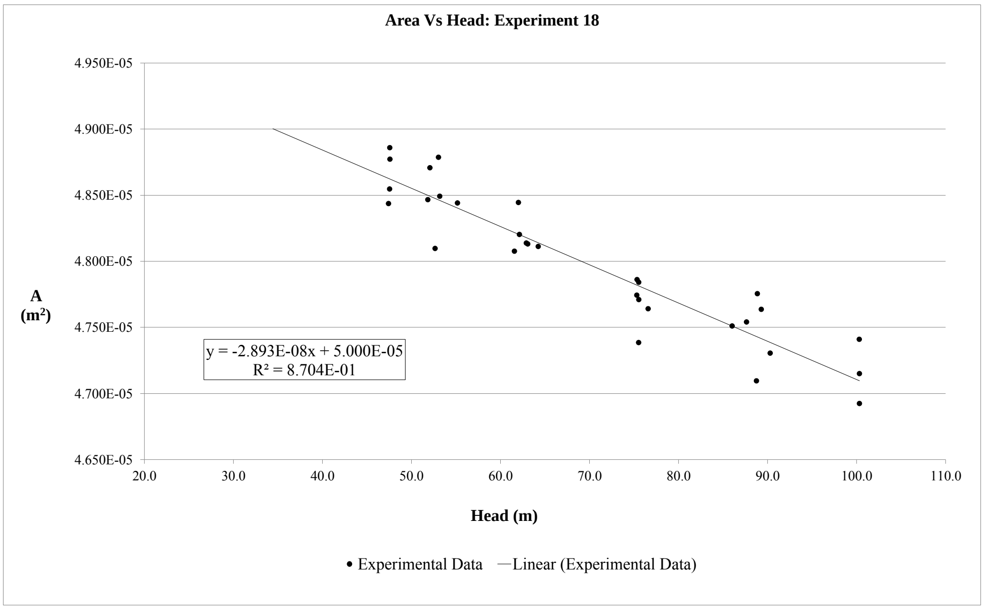
EXPERIMENTAL PARAMETERS	
1 Bar =	10.1937 m
1 l/s =	0.0010 m^3/s
g =	9.81 m/s^2
A_0 =	5.000E-05 m^2
N1 PARAMETERS	
C =	1.764E-04
N1 =	0.4578
R^2 =	0.99876
SSE =	9.404E-05
FAVAD PARAMETERS	
C_dA_0 =	3.473E-05 m^2
C_d =	0.6945
m =	-2.893E-08
R^2 =	0.99869
SSE =	9.404E-05

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
1	1.0261	4.6521	1.0261E-03	47.4225	3.3640E-05	4.8437E-05	1.0318E-03	1.0302E-03
2	1.0736	5.1648	1.0736E-03	52.6486	3.3404E-05	4.8097E-05	1.0824E-03	1.0821E-03
3	1.1604	6.0393	1.1604E-03	61.5625	3.3389E-05	4.8076E-05	1.1627E-03	1.1639E-03
4	1.2667	7.4079	1.2667E-03	75.5133	3.2910E-05	4.7386E-05	1.2767E-03	1.2782E-03
5	1.3649	8.7062	1.3649E-03	88.7483	3.2708E-05	4.7095E-05	1.3746E-03	1.3746E-03
6	1.4458	9.8414	1.4458E-03	100.3199	3.2589E-05	4.6924E-05	1.4540E-03	1.4512E-03
7	1.3691	8.5972	1.3691E-03	87.6375	3.3018E-05	4.7541E-05	1.3667E-03	1.3669E-03
8	1.2746	7.3876	1.2746E-03	75.3067	3.3159E-05	4.7744E-05	1.2751E-03	1.2766E-03
9	1.1757	6.1855	1.1757E-03	63.0532	3.3428E-05	4.8131E-05	1.1755E-03	1.1768E-03
10	1.0734	5.0848	1.0734E-03	51.8331	3.3660E-05	4.8466E-05	1.0747E-03	1.0742E-03
11	1.0298	4.6641	1.0298E-03	47.5447	3.3716E-05	4.8547E-05	1.0330E-03	1.0314E-03
12	1.0877	5.2159	1.0877E-03	53.1688	3.3678E-05	4.8492E-05	1.0873E-03	1.0871E-03
13	1.1745	6.1703	1.1745E-03	62.8985	3.3432E-05	4.8138E-05	1.1742E-03	1.1755E-03
14	1.2826	7.5131	1.2826E-03	76.5862	3.3087E-05	4.7641E-05	1.2850E-03	1.2864E-03
15	1.3828	8.8579	1.3828E-03	90.2949	3.2854E-05	4.7305E-05	1.3856E-03	1.3852E-03
16	1.4528	9.8414	1.4528E-03	100.3199	3.2746E-05	4.7150E-05	1.4540E-03	1.4512E-03
17	1.3848	8.7600	1.3848E-03	89.2966	3.3084E-05	4.7637E-05	1.3785E-03	1.3784E-03
18	1.2780	7.3903	1.2780E-03	75.3348	3.3241E-05	4.7862E-05	1.2753E-03	1.2768E-03
19	1.1735	6.0828	1.1735E-03	62.0057	3.3646E-05	4.8445E-05	1.1665E-03	1.1677E-03
20	1.0813	5.1083	1.0813E-03	52.0721	3.3828E-05	4.8708E-05	1.0769E-03	1.0765E-03
21	1.0349	4.6676	1.0349E-03	47.5799	3.3873E-05	4.8773E-05	1.0334E-03	1.0318E-03
22	1.1068	5.4117	1.1068E-03	55.1654	3.3643E-05	4.8441E-05	1.1058E-03	1.1060E-03
23	1.1862	6.3014	1.1862E-03	64.2342	3.3414E-05	4.8112E-05	1.1856E-03	1.1869E-03
24	1.2756	7.4103	1.2756E-03	75.5387	3.3135E-05	4.7710E-05	1.2769E-03	1.2784E-03
25	1.3556	8.4386	1.3556E-03	86.0206	3.2997E-05	4.7511E-05	1.3551E-03	1.3556E-03
26	1.4607	9.8393	1.4607E-03	100.2988	3.2927E-05	4.7410E-05	1.4538E-03	1.4510E-03
27	1.3848	8.7166	1.3848E-03	88.8537	3.3167E-05	4.7755E-05	1.3754E-03	1.3753E-03
28	1.2790	7.4090	1.2790E-03	75.5246	3.3226E-05	4.7842E-05	1.2768E-03	1.2783E-03
29	1.1687	6.0938	1.1687E-03	62.1182	3.3478E-05	4.8203E-05	1.1675E-03	1.1687E-03
30	1.0929	5.2021	1.0929E-03	53.0282	3.3883E-05	4.8787E-05	1.0859E-03	1.0857E-03
31	1.0365	4.6653	1.0365E-03	47.5569	3.3934E-05	4.8860E-05	1.0331E-03	1.0315E-03



Experiment 18: uPVC Circumferential 50mm

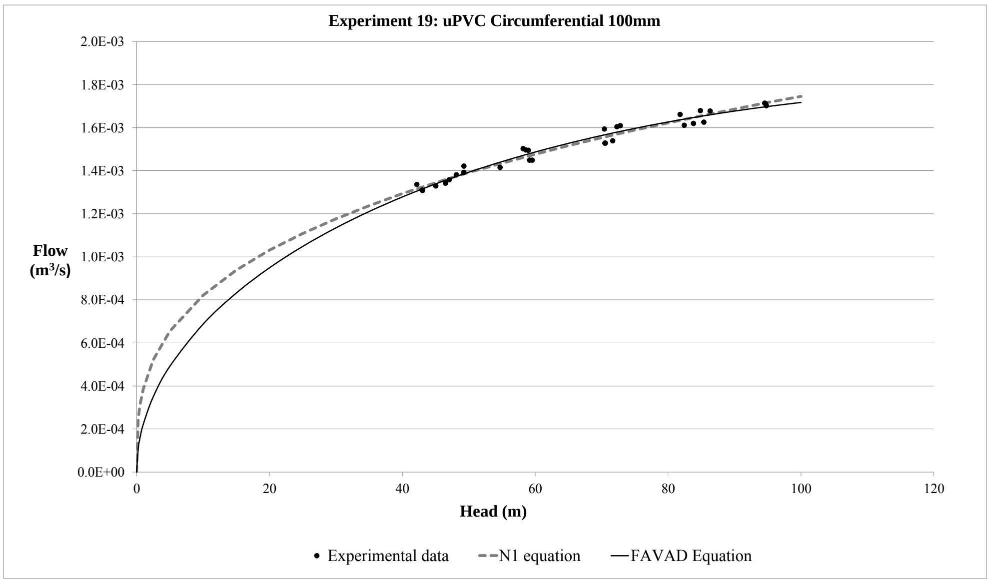




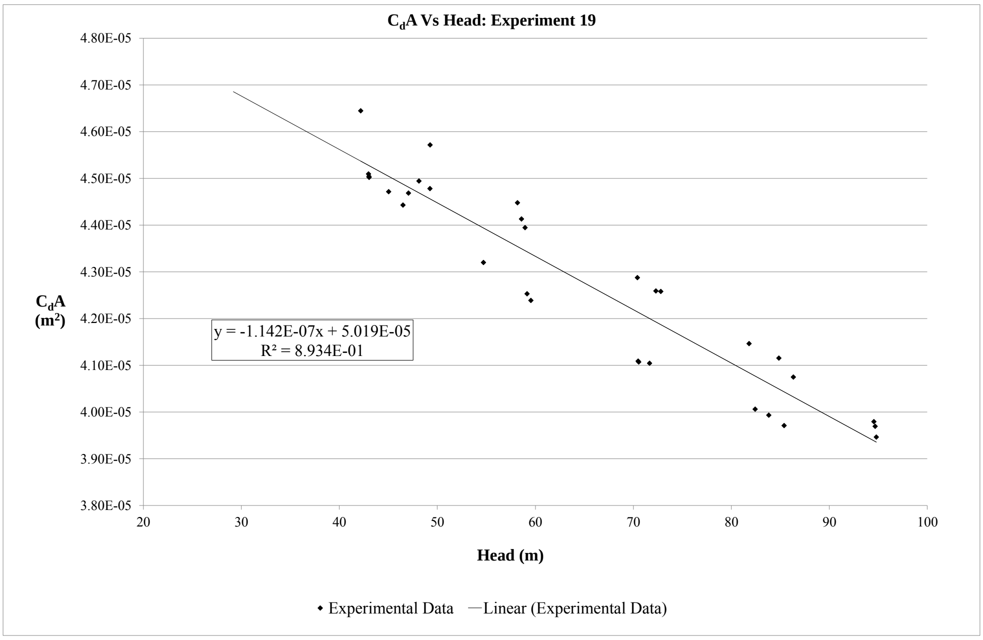
Experiment 19: uPVC Circumferential 100mm

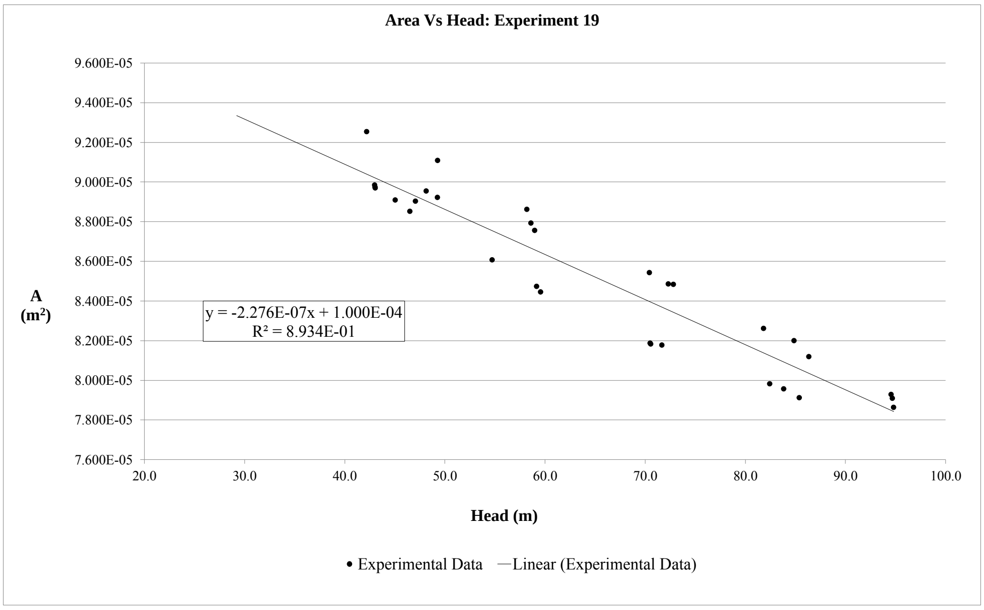
EXPERIMENTAL PARAMETERS	
1 Bar =	10.1937 m
1 l/s =	0.0010 m^3/s
g =	9.81 m/s^2
A_0 =	1.000E-04 m^2
N1 PARAMETERS	
C =	3.866E-04
N1 =	0.3274
R^2 =	0.96681
SSE =	1.417E-04
FAVAD PARAMETERS	
C_dA_0 =	5.019E-05 m^2
C_d =	0.5019
m =	-2.276E-07
R^2 =	0.96691
SSE =	1.418E-04

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
1	1.3362	4.1386	1.3362E-03	42.1878	4.6445E-05	9.2540E-05	1.3160E-03	1.3053E-03
2	1.4213	4.8331	1.4213E-03	49.2671	4.5715E-05	9.1085E-05	1.3845E-03	1.3854E-03
3	1.5027	5.7076	1.5027E-03	58.1813	4.4478E-05	8.8621E-05	1.4620E-03	1.4711E-03
4	1.6093	7.1428	1.6093E-03	72.8110	4.2580E-05	8.4839E-05	1.5734E-03	1.5826E-03
5	1.6771	8.4697	1.6771E-03	86.3370	4.0749E-05	8.1191E-05	1.6637E-03	1.6597E-03
6	1.7020	9.3000	1.7020E-03	94.8012	3.9465E-05	7.8633E-05	1.7154E-03	1.6975E-03
7	1.6254	8.3766	1.6254E-03	85.3879	3.9710E-05	7.9122E-05	1.6576E-03	1.6550E-03
8	1.5282	6.9159	1.5282E-03	70.4981	4.1090E-05	8.1872E-05	1.5569E-03	1.5671E-03
9	1.4489	5.8421	1.4489E-03	59.5522	4.2388E-05	8.4457E-05	1.4732E-03	1.4830E-03
10	1.3578	4.6166	1.3578E-03	47.0597	4.4685E-05	8.9034E-05	1.3639E-03	1.3617E-03
11	1.3095	4.2166	1.3095E-03	42.9822	4.5093E-05	8.9846E-05	1.3240E-03	1.3149E-03
12	1.3811	4.7214	1.3811E-03	48.1282	4.4943E-05	8.9548E-05	1.3740E-03	1.3733E-03
13	1.4962	5.7476	1.4962E-03	58.5891	4.4130E-05	8.7929E-05	1.4654E-03	1.4747E-03
14	1.5937	6.9083	1.5937E-03	70.4208	4.2875E-05	8.5428E-05	1.5563E-03	1.5665E-03
15	1.6793	8.3248	1.6793E-03	84.8606	4.1154E-05	8.1999E-05	1.6543E-03	1.6524E-03
16	1.7140	9.2759	1.7140E-03	94.5552	3.9793E-05	7.9287E-05	1.7139E-03	1.6965E-03
17	1.6195	8.2236	1.6195E-03	83.8285	3.9933E-05	7.9566E-05	1.6477E-03	1.6471E-03
18	1.5390	7.0303	1.5390E-03	71.6651	4.1043E-05	8.1778E-05	1.5652E-03	1.5750E-03
19	1.4489	5.8034	1.4489E-03	59.1585	4.2530E-05	8.4739E-05	1.4700E-03	1.4796E-03
20	1.3419	4.5614	1.3419E-03	46.4972	4.4428E-05	8.8521E-05	1.3586E-03	1.3555E-03
21	1.3083	4.2228	1.3083E-03	43.0454	4.5020E-05	8.9702E-05	1.3247E-03	1.3156E-03
22	1.3920	4.8317	1.3920E-03	49.2530	4.4780E-05	8.9222E-05	1.3844E-03	1.3853E-03
23	1.4947	5.7841	1.4947E-03	58.9617	4.3945E-05	8.7560E-05	1.4684E-03	1.4779E-03
24	1.6041	7.0931	1.6041E-03	72.3048	4.2590E-05	8.4859E-05	1.5698E-03	1.5793E-03
25	1.6613	8.0262	1.6613E-03	81.8166	4.1464E-05	8.2616E-05	1.6346E-03	1.6364E-03
26	1.7109	9.2883	1.7109E-03	94.6817	3.9695E-05	7.9091E-05	1.7147E-03	1.6970E-03
27	1.6111	8.0869	1.6111E-03	82.4352	4.0062E-05	7.9822E-05	1.6387E-03	1.6397E-03
28	1.5281	6.9214	1.5281E-03	70.5543	4.1071E-05	8.1832E-05	1.5573E-03	1.5675E-03
29	1.4154	5.3676	1.4154E-03	54.7155	4.3199E-05	8.6074E-05	1.4329E-03	1.4396E-03
30	1.3293	4.4186	1.3293E-03	45.0420	4.4715E-05	8.9094E-05	1.3445E-03	1.3390E-03
31	1.3086	4.2207	1.3086E-03	43.0241	4.5042E-05	8.9745E-05	1.3245E-03	1.3154E-03



Experiment 19: uPVC Circumferential 100mm

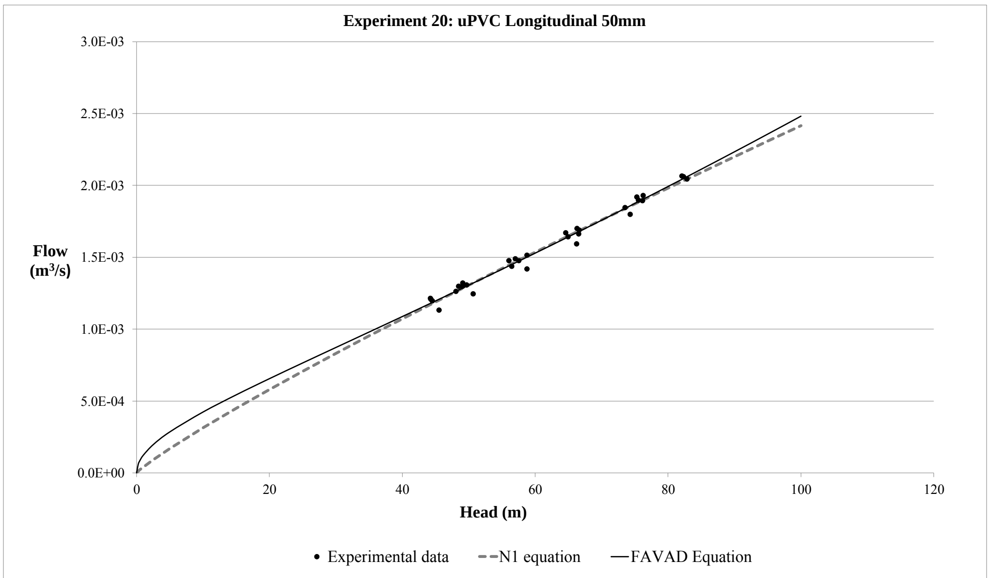




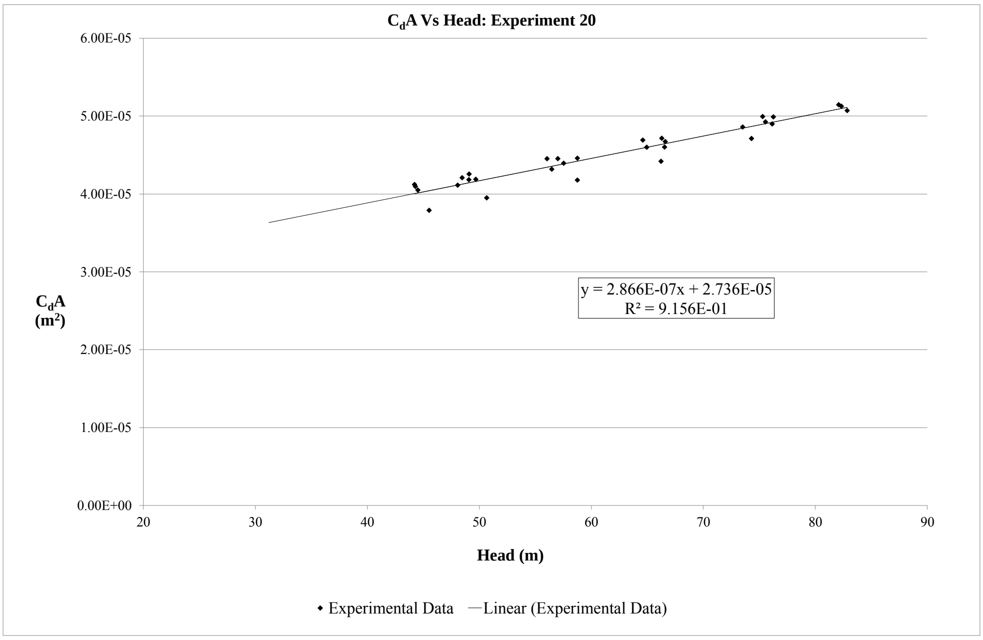
Experiment 20: uPVC Longitudinal 50mm

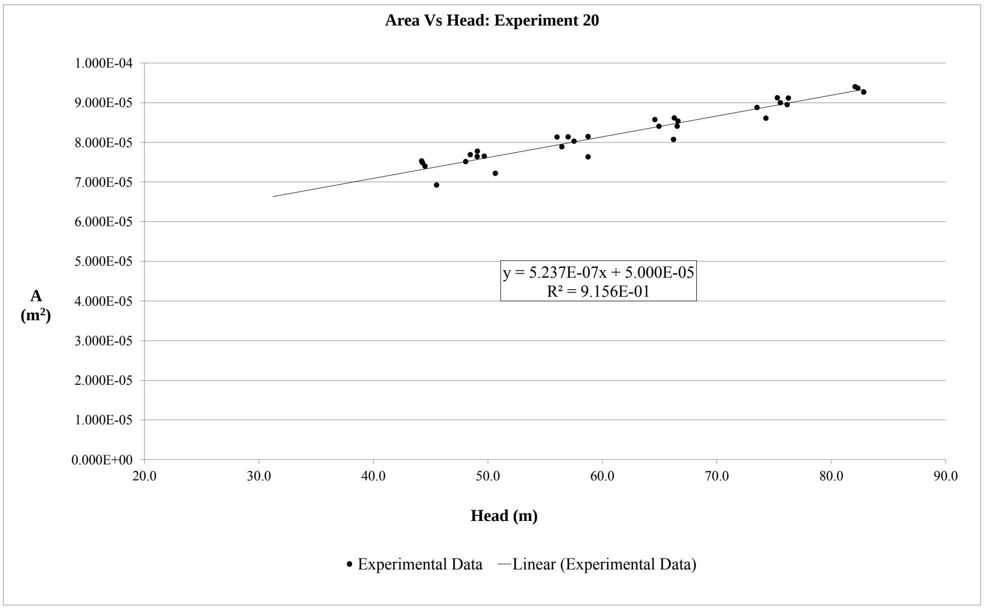
EXPERIMENTAL PARAMETERS	
1 Bar =	10.1937 m
1 l/s =	0.0010 m^3/s
g =	9.81 m/s^2
A_0 =	5.000E-05 m^2
N1 PARAMETERS	
C =	4.084E-05
N1 =	0.8859
R^2 =	0.98276
SSE =	1.579E-04
FAVAD PARAMETERS	
C_dA_0 =	2.736E-05 m^2
C_d =	0.5472
m =	5.237E-07
R^2 =	0.98398
SSE =	1.580E-04

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
1	1.1324	4.4657	1.1324E-03	45.5221	3.7892E-05	6.9240E-05	1.2025E-03	1.2076E-03
2	1.2452	4.9696	1.2452E-03	50.6588	3.9497E-05	7.2173E-05	1.3219E-03	1.3203E-03
3	1.4184	5.7648	1.4184E-03	58.7648	4.1773E-05	7.6332E-05	1.5077E-03	1.5009E-03
4	1.5926	6.4972	1.5926E-03	66.2308	4.4180E-05	8.0732E-05	1.6762E-03	1.6706E-03
5	1.7986	7.2893	1.7986E-03	74.3046	4.7107E-05	8.6079E-05	1.8560E-03	1.8578E-03
6	2.0442	8.1276	2.0442E-03	82.8500	5.0703E-05	9.2651E-05	2.0439E-03	2.0605E-03
7	1.8963	7.4121	1.8963E-03	75.5570	4.9252E-05	8.9999E-05	1.8837E-03	1.8872E-03
8	1.6889	6.5345	1.6889E-03	66.6104	4.6719E-05	8.5370E-05	1.6847E-03	1.6793E-03
9	1.5139	5.7648	1.5139E-03	58.7648	4.4584E-05	8.1470E-05	1.5077E-03	1.5009E-03
10	1.3074	4.8745	1.3074E-03	49.6889	4.1873E-05	7.6515E-05	1.2995E-03	1.2990E-03
11	1.1967	4.3669	1.1967E-03	44.5147	4.0494E-05	7.3995E-05	1.1789E-03	1.1857E-03
12	1.2627	4.7159	1.2627E-03	48.0720	4.1116E-05	7.5132E-05	1.2619E-03	1.2634E-03
13	1.4369	5.5400	1.4369E-03	56.4730	4.3166E-05	7.8879E-05	1.4555E-03	1.4495E-03
14	1.6625	6.5283	1.6625E-03	66.5472	4.6010E-05	8.4076E-05	1.6833E-03	1.6778E-03
15	1.8934	7.4710	1.8934E-03	76.1573	4.8981E-05	8.9505E-05	1.8970E-03	1.9014E-03
16	2.0602	8.0766	2.0602E-03	82.3298	5.1261E-05	9.3670E-05	2.0325E-03	2.0480E-03
17	1.9297	7.4807	1.9297E-03	76.2558	4.9889E-05	9.1163E-05	1.8991E-03	1.9037E-03
18	1.7002	6.5036	1.7002E-03	66.2953	4.7143E-05	8.6146E-05	1.6776E-03	1.6721E-03
19	1.4893	5.5931	1.4893E-03	57.0143	4.4530E-05	8.1370E-05	1.4678E-03	1.4616E-03
20	1.2977	4.7552	1.2977E-03	48.4727	4.2081E-05	7.6895E-05	1.2713E-03	1.2722E-03
21	1.2075	4.3455	1.2075E-03	44.2968	4.0961E-05	7.4848E-05	1.1737E-03	1.1809E-03
22	1.2978	4.8138	1.2978E-03	49.0703	4.1827E-05	7.6431E-05	1.2851E-03	1.2854E-03
23	1.4762	5.6441	1.4762E-03	57.5345	4.3937E-05	8.0287E-05	1.4797E-03	1.4733E-03
24	1.6419	6.3717	1.6419E-03	64.9513	4.5995E-05	8.4048E-05	1.6475E-03	1.6413E-03
25	1.8453	7.2124	1.8453E-03	73.5210	4.8586E-05	8.8782E-05	1.8387E-03	1.8395E-03
26	2.0649	8.0531	2.0649E-03	82.0908	5.1453E-05	9.4020E-05	2.0273E-03	2.0423E-03
27	1.9190	7.3867	1.9190E-03	75.2973	4.9928E-05	9.1234E-05	1.8780E-03	1.8811E-03
28	1.6701	6.3371	1.6701E-03	64.5988	4.6913E-05	8.5725E-05	1.6396E-03	1.6332E-03
29	1.4761	5.4986	1.4761E-03	56.0507	4.4513E-05	8.1340E-05	1.4458E-03	1.4401E-03
30	1.3207	4.8159	1.3207E-03	49.0914	4.2556E-05	7.7762E-05	1.2856E-03	1.2858E-03
31	1.2138	4.3379	1.2138E-03	44.2195	4.1210E-05	7.5305E-05	1.1719E-03	1.1792E-03



Experiment 20: uPVC Longitudinal 50mm

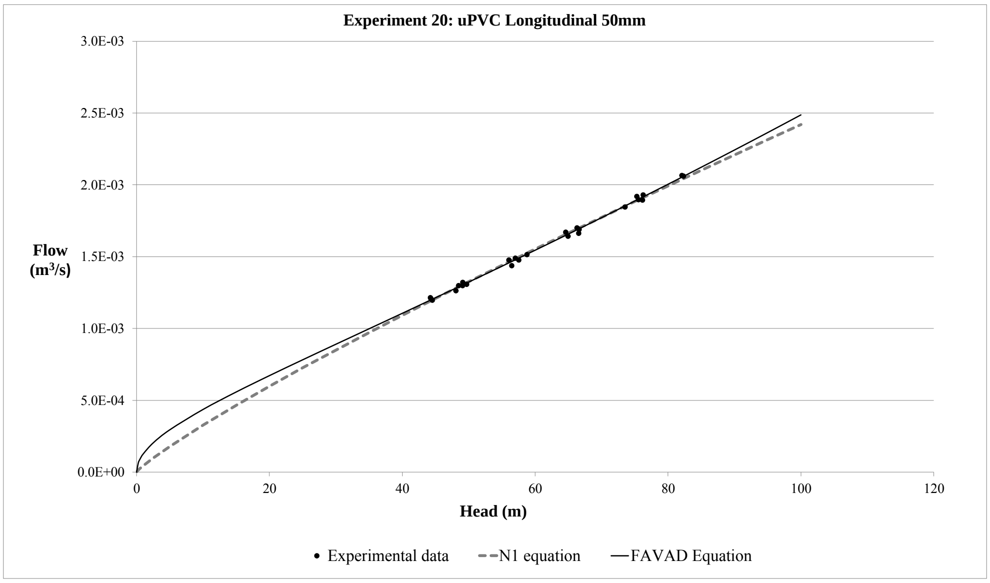




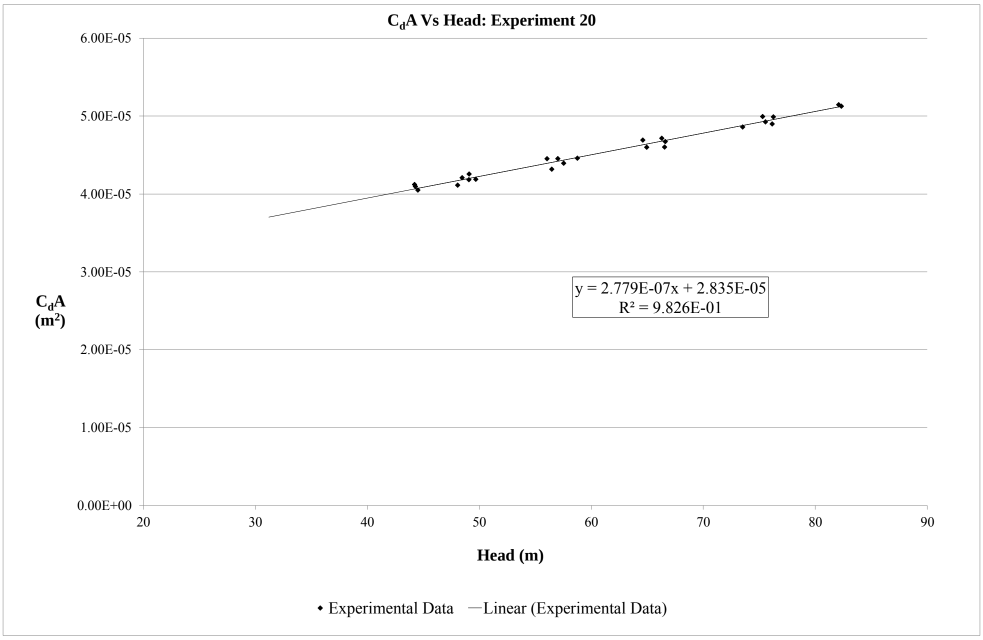
Experiment 20 (Omitted): uPVC Longitudinal 50mm

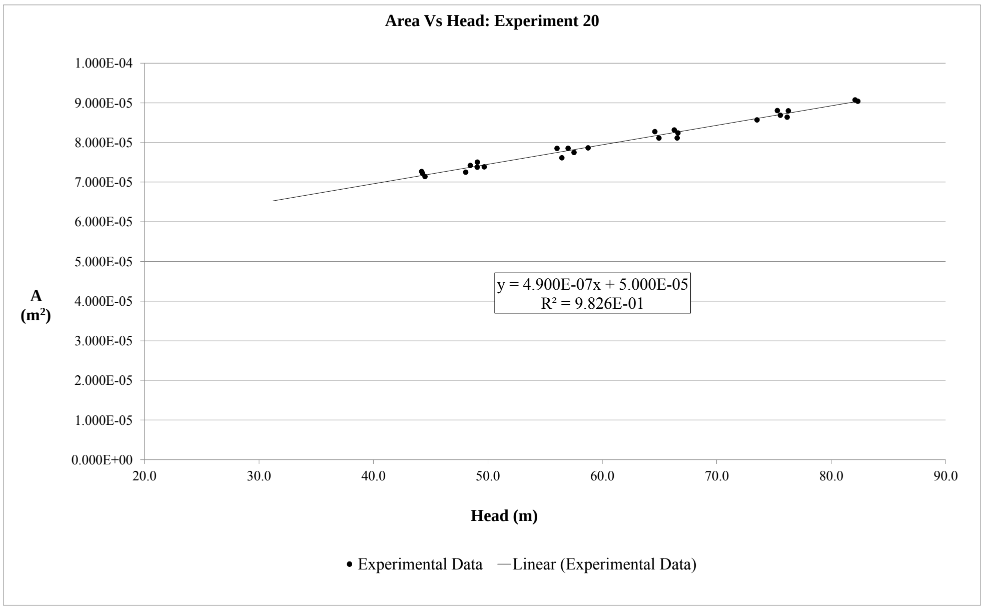
EXPERIMENTAL PARAMETERS	
1 Bar =	10.1937 m
1 l/s =	0.0010 m^3/s
g =	9.81 m/s^2
A_0 =	5.000E-05 m^2
N1 PARAMETERS	
C =	4.421E-05
N1 =	0.8691
R^2 =	0.99577
SSE =	1.284E-04
FAVAD PARAMETERS	
C_dA_0 =	2.835E-05 m^2
C_d =	0.5671
m =	4.900E-07
R^2 =	0.99683
SSE =	1.284E-04

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
7	1.8963	7.4121	1.8963E-03	75.5570	4.9252E-05	8.6851E-05	1.8964E-03	1.9001E-03
8	1.6889	6.5345	1.6889E-03	66.6104	4.6719E-05	8.2384E-05	1.6996E-03	1.6942E-03
9	1.5139	5.7648	1.5139E-03	58.7648	4.4584E-05	7.8620E-05	1.5242E-03	1.5173E-03
10	1.3074	4.8745	1.3074E-03	49.6889	4.1873E-05	7.3839E-05	1.3174E-03	1.3164E-03
11	1.1967	4.3669	1.1967E-03	44.5147	4.0494E-05	7.1407E-05	1.1974E-03	1.2035E-03
12	1.2627	4.7159	1.2627E-03	48.0720	4.1116E-05	7.2504E-05	1.2801E-03	1.2810E-03
13	1.4369	5.5400	1.4369E-03	56.4730	4.3166E-05	7.6120E-05	1.4724E-03	1.4662E-03
14	1.6625	6.5283	1.6625E-03	66.5472	4.6010E-05	8.1135E-05	1.6982E-03	1.6927E-03
15	1.8934	7.4710	1.8934E-03	76.1573	4.8981E-05	8.6374E-05	1.9094E-03	1.9141E-03
16	2.0602	8.0766	2.0602E-03	82.3298	5.1261E-05	9.0394E-05	2.0432E-03	2.0591E-03
17	1.9297	7.4807	1.9297E-03	76.2558	4.9889E-05	8.7974E-05	1.9116E-03	1.9164E-03
18	1.7002	6.5036	1.7002E-03	66.2953	4.7143E-05	8.3133E-05	1.6926E-03	1.6870E-03
19	1.4893	5.5931	1.4893E-03	57.0143	4.4530E-05	7.8524E-05	1.4847E-03	1.4782E-03
20	1.2977	4.7552	1.2977E-03	48.4727	4.2081E-05	7.4205E-05	1.2894E-03	1.2898E-03
21	1.2075	4.3455	1.2075E-03	44.2968	4.0961E-05	7.2230E-05	1.1923E-03	1.1988E-03
22	1.2978	4.8138	1.2978E-03	49.0703	4.1827E-05	7.3757E-05	1.3032E-03	1.3029E-03
23	1.4762	5.6441	1.4762E-03	57.5345	4.3937E-05	7.7479E-05	1.4965E-03	1.4898E-03
24	1.6419	6.3717	1.6419E-03	64.9513	4.5995E-05	8.1108E-05	1.6628E-03	1.6565E-03
25	1.8453	7.2124	1.8453E-03	73.5210	4.8586E-05	8.5676E-05	1.8519E-03	1.8528E-03
26	2.0649	8.0531	2.0649E-03	82.0908	5.1453E-05	9.0732E-05	2.0381E-03	2.0534E-03
27	1.9190	7.3867	1.9190E-03	75.2973	4.9928E-05	8.8043E-05	1.8907E-03	1.8940E-03
28	1.6701	6.3371	1.6701E-03	64.5988	4.6913E-05	8.2726E-05	1.6549E-03	1.6485E-03
29	1.4761	5.4986	1.4761E-03	56.0507	4.4513E-05	7.8495E-05	1.4629E-03	1.4568E-03
30	1.3207	4.8159	1.3207E-03	49.0914	4.2556E-05	7.5042E-05	1.3037E-03	1.3033E-03
31	1.2138	4.3379	1.2138E-03	44.2195	4.1210E-05	7.2671E-05	1.1905E-03	1.1971E-03



Experiment 20 (Omitted): uPVC Longitudinal 50mm

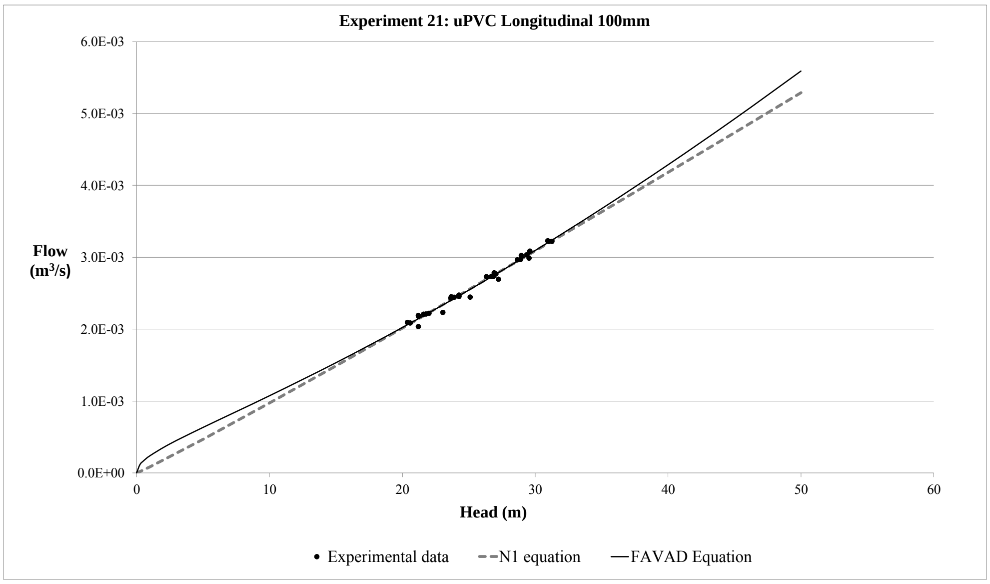




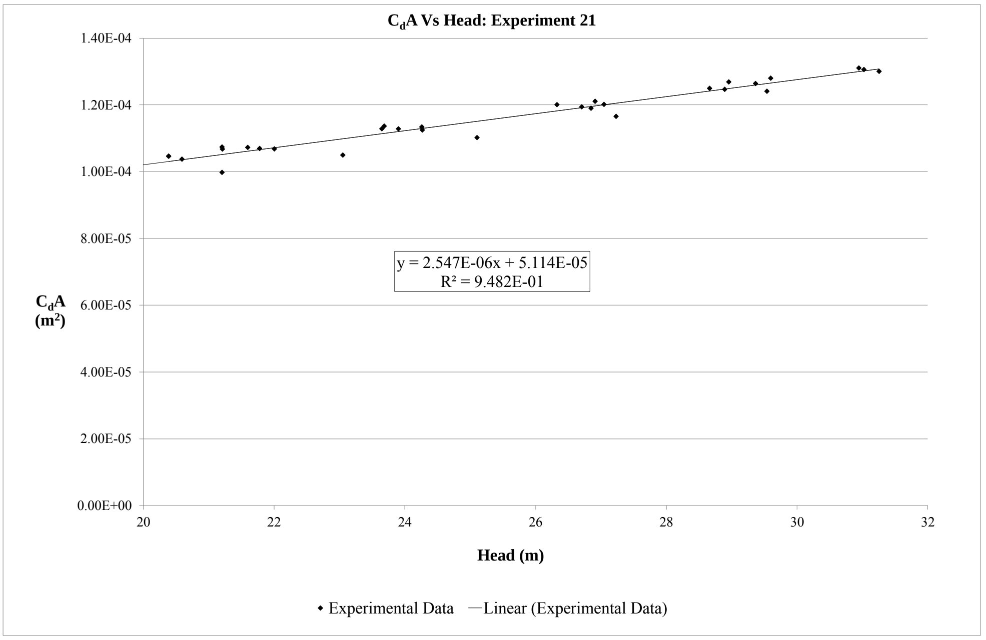
Experiment 21: uPVC Longitudinal 100mm

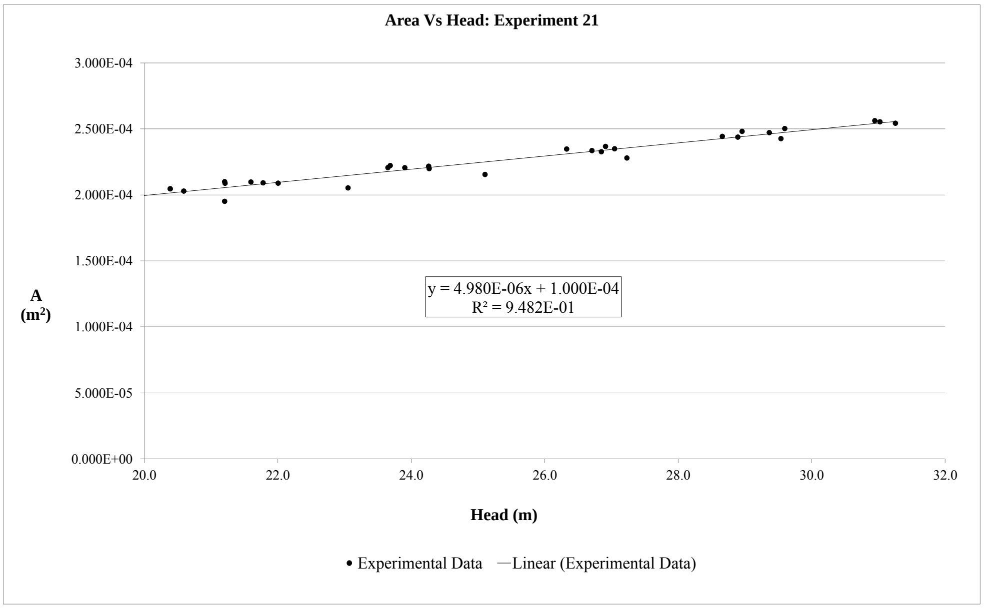
EXPERIMENTAL PARAMETERS	
1 Bar =	10.1937 m
1 l/s =	0.0010 m^3/s
g =	9.81 m/s^2
A_0 =	1.000E-04 m^2
N1 PARAMETERS	
C =	8.581E-05
N1 =	1.0535
R^2 =	0.98519
SSE =	4.259E-04
FAVAD PARAMETERS	
C_dA_0 =	5.114E-05 m^2
C_d =	0.5114
m =	4.980E-06
R^2 =	0.98585
SSE =	4.260E-04

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
1	2.0353	2.0800	2.0353E-03	21.2029	9.9787E-05	1.9512E-04	2.1423E-03	2.1444E-03
2	2.2324	2.2614	2.2324E-03	23.0518	1.0497E-04	2.0526E-04	2.3396E-03	2.3361E-03
3	2.4459	2.4628	2.4459E-03	25.1046	1.1021E-04	2.1550E-04	2.5595E-03	2.5539E-03
4	2.6943	2.6714	2.6943E-03	27.2317	1.1656E-04	2.2792E-04	2.7885E-03	2.7852E-03
5	2.9873	2.8979	2.9873E-03	29.5398	1.2409E-04	2.4264E-04	3.0381E-03	3.0423E-03
6	3.2202	3.0662	3.2202E-03	31.2559	1.3004E-04	2.5427E-04	3.2243E-03	3.2377E-03
7	3.0339	2.8807	3.0339E-03	29.3651	1.2640E-04	2.4715E-04	3.0191E-03	3.0226E-03
8	2.7675	2.6533	2.7675E-03	27.0472	1.2014E-04	2.3491E-04	2.7686E-03	2.7649E-03
9	2.4737	2.3800	2.4737E-03	24.2610	1.1338E-04	2.2170E-04	2.4690E-03	2.4638E-03
10	2.2106	2.1366	2.2106E-03	21.7793	1.0694E-04	2.0910E-04	2.2037E-03	2.2037E-03
11	2.0852	2.0200	2.0852E-03	20.5912	1.0374E-04	2.0285E-04	2.0773E-03	2.0820E-03
12	2.2192	2.1586	2.2192E-03	22.0043	1.0680E-04	2.0884E-04	2.2277E-03	2.2270E-03
13	2.4541	2.3807	2.4541E-03	24.2680	1.1247E-04	2.1991E-04	2.4698E-03	2.4645E-03
14	2.7310	2.6338	2.7310E-03	26.8480	1.1899E-04	2.3267E-04	2.7472E-03	2.7430E-03
15	2.9679	2.8345	2.9679E-03	28.8938	1.2465E-04	2.4373E-04	2.9681E-03	2.9697E-03
16	3.2218	3.0434	3.2218E-03	31.0239	1.3059E-04	2.5534E-04	3.1991E-03	3.2110E-03
17	3.0844	2.9034	3.0844E-03	29.5968	1.2799E-04	2.5027E-04	3.0442E-03	3.0487E-03
18	2.7820	2.6400	2.7820E-03	26.9113	1.2107E-04	2.3673E-04	2.7540E-03	2.7500E-03
19	2.4308	2.3200	2.4308E-03	23.6493	1.1284E-04	2.2065E-04	2.4035E-03	2.3990E-03
20	2.1780	2.0807	2.1780E-03	21.2097	1.0677E-04	2.0877E-04	2.1430E-03	2.1451E-03
21	2.0925	2.0000	2.0925E-03	20.3874	1.0462E-04	2.0457E-04	2.0556E-03	2.0613E-03
22	2.2077	2.1186	2.2077E-03	21.5965	1.0725E-04	2.0971E-04	2.1842E-03	2.1849E-03
23	2.4431	2.3448	2.4431E-03	23.9024	1.1282E-04	2.2059E-04	2.4306E-03	2.4257E-03
24	2.7339	2.6200	2.7339E-03	26.7074	1.1943E-04	2.3353E-04	2.7320E-03	2.7277E-03
25	2.9632	2.8117	2.9632E-03	28.6618	1.2496E-04	2.4434E-04	2.9430E-03	2.9437E-03
26	3.2291	3.0359	3.2291E-03	30.9466	1.3105E-04	2.5624E-04	3.1907E-03	3.2022E-03
27	3.0245	2.8407	3.0245E-03	28.9571	1.2689E-04	2.4811E-04	2.9750E-03	2.9768E-03
28	2.7287	2.5828	2.7287E-03	26.3278	1.2006E-04	2.3476E-04	2.6911E-03	2.6862E-03
29	2.4500	2.3234	2.4500E-03	23.6845	1.1365E-04	2.2223E-04	2.4073E-03	2.4027E-03
30	2.1902	2.0800	2.1902E-03	21.2029	1.0739E-04	2.0997E-04	2.1423E-03	2.1444E-03
31	2.0928	2.0000	2.0928E-03	20.3874	1.0464E-04	2.0461E-04	2.0556E-03	2.0613E-03



Experiment 21: uPVC Longitudinal 100mm

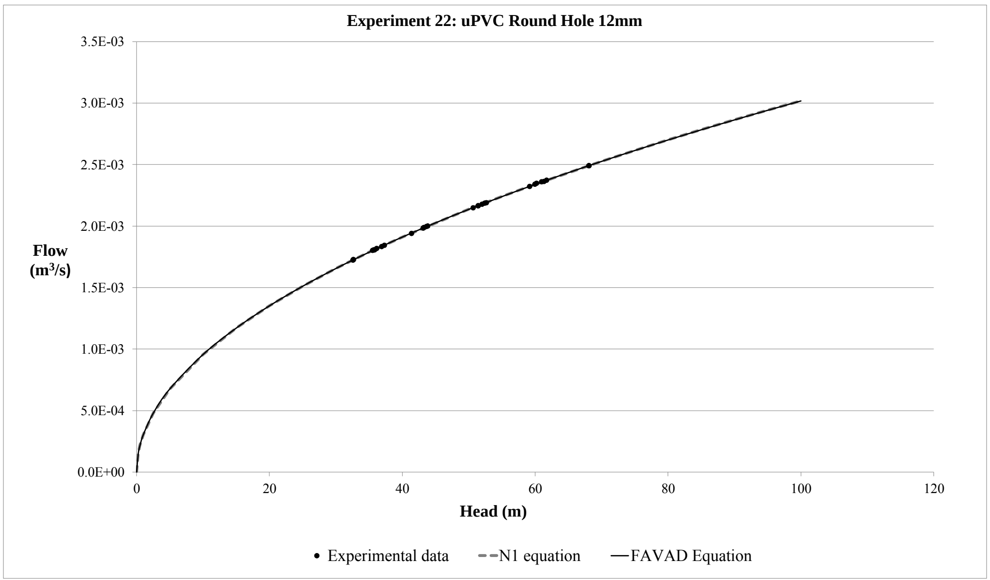




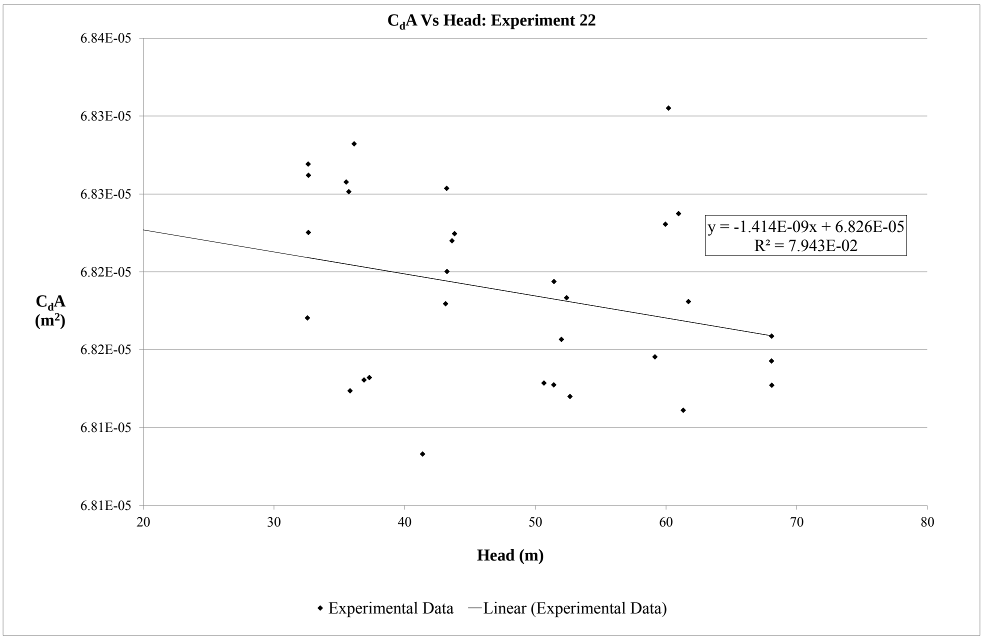
Experiment 22: uPVC Round Hole 12mm

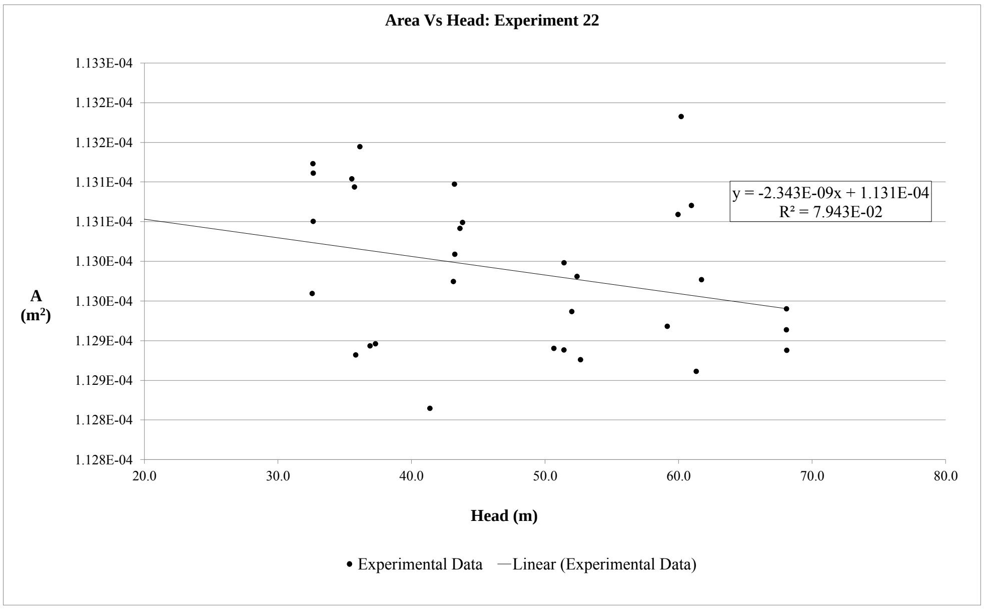
EXPERIMENTAL PARAMETERS	
1 Bar =	10.1937 m
1 l/s =	0.0010 m^3/s
g =	9.81 m/s^2
A_0 =	1.131E-04 m^2
N1 PARAMETERS	
C =	3.032E-04
N1 =	0.4990
R^2 =	0.99996
SSE =	2.708E-04
FAVAD PARAMETERS	
C_dA_0 =	6.826E-05 m^2
C_d =	0.6035
m =	-2.343E-09
R^2 =	0.99995
SSE =	2.708E-04

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
1	1.7231	3.1945	1.7231E-03	32.5635	6.8170E-05	1.1296E-04	1.7242E-03	1.7241E-03
2	1.8432	3.6593	1.8432E-03	37.3018	6.8132E-05	1.1290E-04	1.8451E-03	1.8451E-03
3	1.9959	4.2800	1.9959E-03	43.6290	6.8220E-05	1.1304E-04	1.9951E-03	1.9952E-03
4	2.1861	5.1400	2.1861E-03	52.3955	6.8183E-05	1.1298E-04	2.1860E-03	2.1861E-03
5	2.3216	5.8034	2.3216E-03	59.1585	6.8145E-05	1.1292E-04	2.3225E-03	2.3225E-03
6	2.4912	6.6793	2.4912E-03	68.0868	6.8159E-05	1.1294E-04	2.4912E-03	2.4912E-03
7	2.3475	5.9055	2.3475E-03	60.1990	6.8305E-05	1.1318E-04	2.3428E-03	2.3428E-03
8	2.1661	5.0448	2.1661E-03	51.4254	6.8194E-05	1.1300E-04	2.1657E-03	2.1658E-03
9	1.9835	4.2317	1.9835E-03	43.1368	6.8179E-05	1.1297E-04	1.9839E-03	1.9839E-03
10	1.8181	3.5448	1.8181E-03	36.1348	6.8282E-05	1.1314E-04	1.8161E-03	1.8160E-03
11	1.7271	3.2000	1.7271E-03	32.6198	6.8269E-05	1.1312E-04	1.7257E-03	1.7256E-03
12	1.8022	3.4855	1.8022E-03	35.5302	6.8258E-05	1.1310E-04	1.8008E-03	1.8008E-03
13	1.9399	4.0593	1.9399E-03	41.3793	6.8083E-05	1.1281E-04	1.9431E-03	1.9431E-03
14	2.1770	5.1014	2.1770E-03	52.0018	6.8157E-05	1.1294E-04	2.1778E-03	2.1778E-03
15	2.3600	5.9807	2.3600E-03	60.9652	6.8237E-05	1.1307E-04	2.3576E-03	2.3576E-03
16	2.4905	6.6786	2.4905E-03	68.0797	6.8143E-05	1.1291E-04	2.4911E-03	2.4910E-03
17	2.3402	5.8821	2.3402E-03	59.9599	6.8231E-05	1.1306E-04	2.3381E-03	2.3382E-03
18	2.1480	4.9703	2.1480E-03	50.6661	6.8129E-05	1.1289E-04	2.1497E-03	2.1498E-03
19	1.9865	4.2421	1.9865E-03	43.2423	6.8200E-05	1.1301E-04	1.9863E-03	1.9863E-03
20	1.8070	3.5048	1.8070E-03	35.7271	6.8251E-05	1.1309E-04	1.8058E-03	1.8058E-03
21	1.7275	3.2021	1.7275E-03	32.6409	6.8262E-05	1.1311E-04	1.7262E-03	1.7261E-03
22	1.8330	3.6193	1.8330E-03	36.8941	6.8131E-05	1.1289E-04	1.8350E-03	1.8350E-03
23	2.0006	4.2993	2.0006E-03	43.8258	6.8224E-05	1.1305E-04	1.9996E-03	1.9997E-03
24	2.1895	5.1655	2.1895E-03	52.6556	6.8120E-05	1.1288E-04	2.1914E-03	2.1915E-03
25	2.3626	6.0160	2.3626E-03	61.3252	6.8111E-05	1.1286E-04	2.3646E-03	2.3646E-03
26	2.4903	6.6807	2.4903E-03	68.1011	6.8127E-05	1.1289E-04	2.4915E-03	2.4914E-03
27	2.3726	6.0545	2.3726E-03	61.7175	6.8181E-05	1.1298E-04	2.3721E-03	2.3721E-03
28	2.1639	5.0441	2.1639E-03	51.4183	6.8127E-05	1.1289E-04	2.1656E-03	2.1656E-03
29	1.9876	4.2400	1.9876E-03	43.2212	6.8254E-05	1.1310E-04	1.9858E-03	1.9858E-03
30	1.8061	3.5145	1.8061E-03	35.8255	6.8124E-05	1.1288E-04	1.8083E-03	1.8083E-03
31	1.7264	3.2014	1.7264E-03	32.6338	6.8225E-05	1.1305E-04	1.7260E-03	1.7259E-03



Experiment 22: uPVC Round Hole 12mm

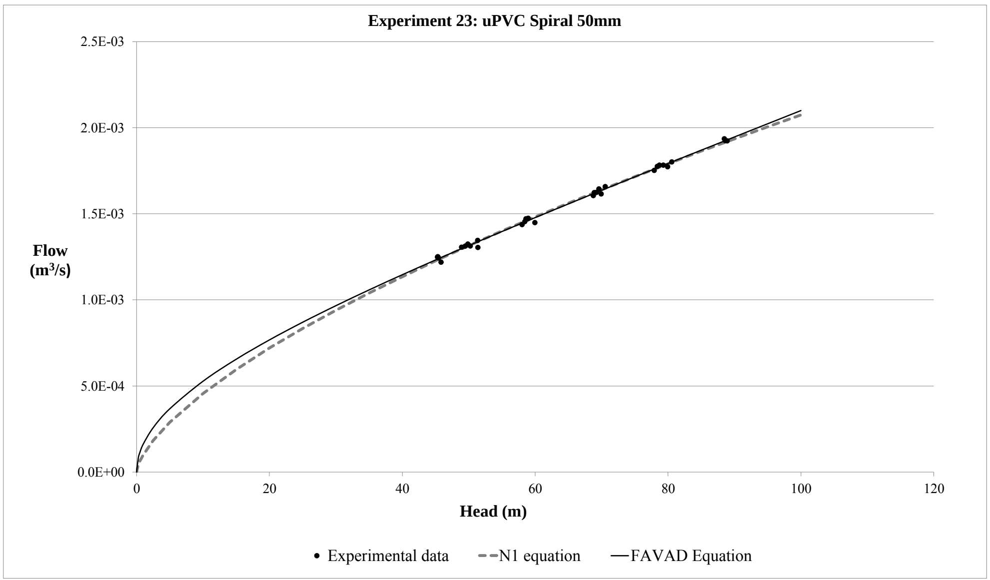




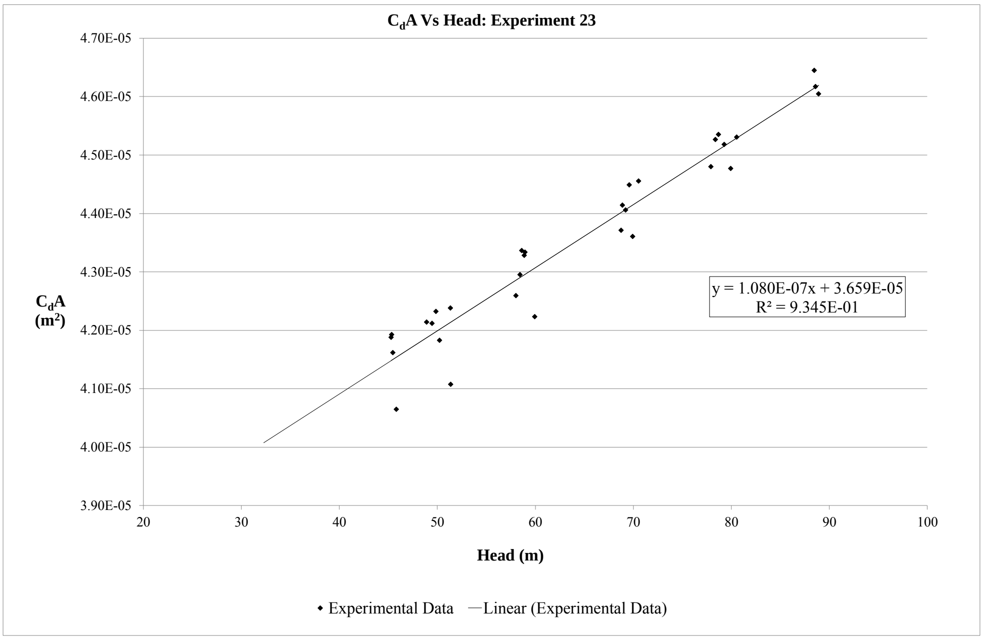
Experiment 23: uPVC Spiral 50mm

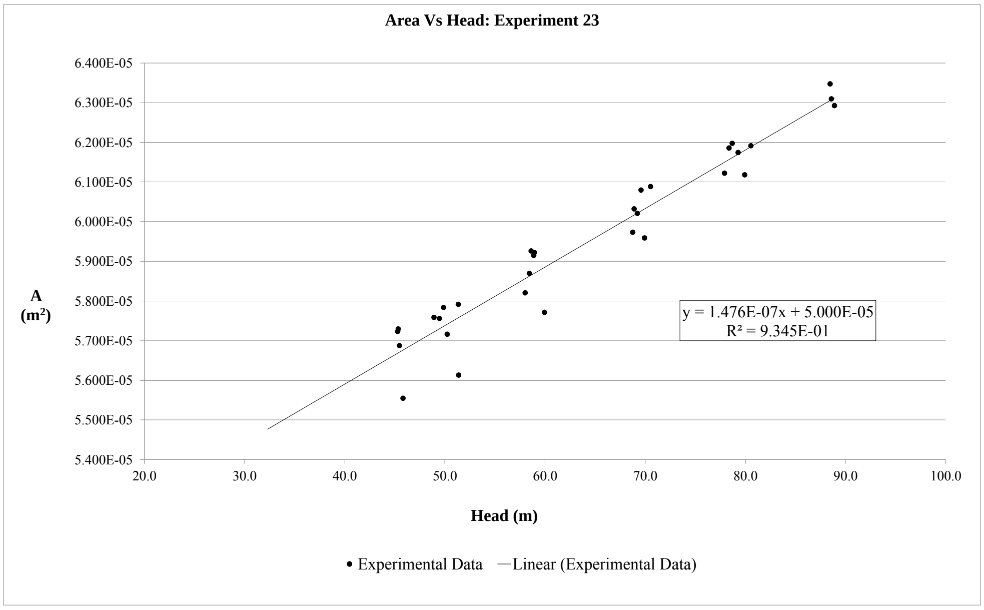
EXPERIMENTAL PARAMETERS	
1 Bar =	10.1937 m
1 l/s =	0.0010 m^3/s
g =	9.81 m/s^2
A_0 =	5.000E-05 m^2
N1 PARAMETERS	
C =	1.004E-04
N1 =	0.6574
R^2 =	0.99589
SSE =	1.507E-04
FAVAD PARAMETERS	
C_dA_0 =	3.659E-05 m^2
C_d =	0.7318
m =	1.476E-07
R^2 =	0.99637
SSE =	1.507E-04

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
1	1.2188	4.4952	1.2188E-03	45.8223	4.0648E-05	5.5547E-05	1.2414E-03	1.2455E-03
2	1.3040	5.0393	1.3040E-03	51.3691	4.1075E-05	5.6131E-05	1.3382E-03	1.3377E-03
3	1.4484	5.8808	1.4484E-03	59.9467	4.2233E-05	5.7713E-05	1.4812E-03	1.4769E-03
4	1.6152	6.8607	1.6152E-03	69.9359	4.3605E-05	5.9588E-05	1.6392E-03	1.6352E-03
5	1.7730	7.8421	1.7730E-03	79.9395	4.4769E-05	6.1179E-05	1.7897E-03	1.7910E-03
6	1.9231	8.7214	1.9231E-03	88.9035	4.6046E-05	6.2925E-05	1.9193E-03	1.9292E-03
7	1.8011	7.9023	1.8011E-03	80.5536	4.5306E-05	6.1913E-05	1.7988E-03	1.8005E-03
8	1.6236	6.7900	1.6236E-03	69.2151	4.4058E-05	6.0207E-05	1.6280E-03	1.6238E-03
9	1.4544	5.7331	1.4544E-03	58.4414	4.2952E-05	5.8696E-05	1.4567E-03	1.4527E-03
10	1.3121	4.8521	1.3121E-03	49.4612	4.2119E-05	5.7558E-05	1.3054E-03	1.3062E-03
11	1.2430	4.4600	1.2430E-03	45.4638	4.1617E-05	5.6872E-05	1.2350E-03	1.2394E-03
12	1.3131	4.9276	1.3131E-03	50.2302	4.1828E-05	5.7160E-05	1.3187E-03	1.3190E-03
13	1.4371	5.6917	1.4371E-03	58.0196	4.2593E-05	5.8205E-05	1.4497E-03	1.4459E-03
14	1.6054	6.7448	1.6054E-03	68.7546	4.3711E-05	5.9734E-05	1.6209E-03	1.6166E-03
15	1.7517	7.6441	1.7517E-03	77.9219	4.4801E-05	6.1223E-05	1.7599E-03	1.7597E-03
16	1.9249	8.6910	1.9249E-03	88.5936	4.6171E-05	6.3095E-05	1.9149E-03	1.9244E-03
17	1.7750	7.6886	1.7750E-03	78.3748	4.5265E-05	6.1857E-05	1.7666E-03	1.7668E-03
18	1.6439	6.8269	1.6439E-03	69.5912	4.4489E-05	6.0796E-05	1.6338E-03	1.6297E-03
19	1.4706	5.7503	1.4706E-03	58.6172	4.3365E-05	5.9261E-05	1.4595E-03	1.4555E-03
20	1.3055	4.7986	1.3055E-03	48.9156	4.2139E-05	5.7586E-05	1.2959E-03	1.2972E-03
21	1.2484	4.4428	1.2484E-03	45.2881	4.1879E-05	5.7230E-05	1.2319E-03	1.2365E-03
22	1.3451	5.0366	1.3451E-03	51.3410	4.2381E-05	5.7916E-05	1.3378E-03	1.3373E-03
23	1.4710	5.7752	1.4710E-03	58.8703	4.3282E-05	5.9148E-05	1.4637E-03	1.4596E-03
24	1.6229	6.7586	1.6229E-03	68.8952	4.4141E-05	6.0321E-05	1.6231E-03	1.6188E-03
25	1.7819	7.7772	1.7819E-03	79.2787	4.5181E-05	6.1742E-05	1.7800E-03	1.7808E-03
26	1.9351	8.6786	1.9351E-03	88.4671	4.6448E-05	6.3473E-05	1.9131E-03	1.9225E-03
27	1.7820	7.7200	1.7820E-03	78.6952	4.5351E-05	6.1975E-05	1.7714E-03	1.7717E-03
28	1.6575	6.9200	1.6575E-03	70.5403	4.4554E-05	6.0885E-05	1.6485E-03	1.6446E-03
29	1.4738	5.7828	1.4738E-03	58.9476	4.3337E-05	5.9222E-05	1.4649E-03	1.4608E-03
30	1.3238	4.8917	1.3238E-03	49.8647	4.2322E-05	5.7835E-05	1.3123E-03	1.3129E-03
31	1.2505	4.4483	1.2505E-03	45.3443	4.1926E-05	5.7294E-05	1.2329E-03	1.2374E-03



Experiment 23: uPVC Spiral 50mm

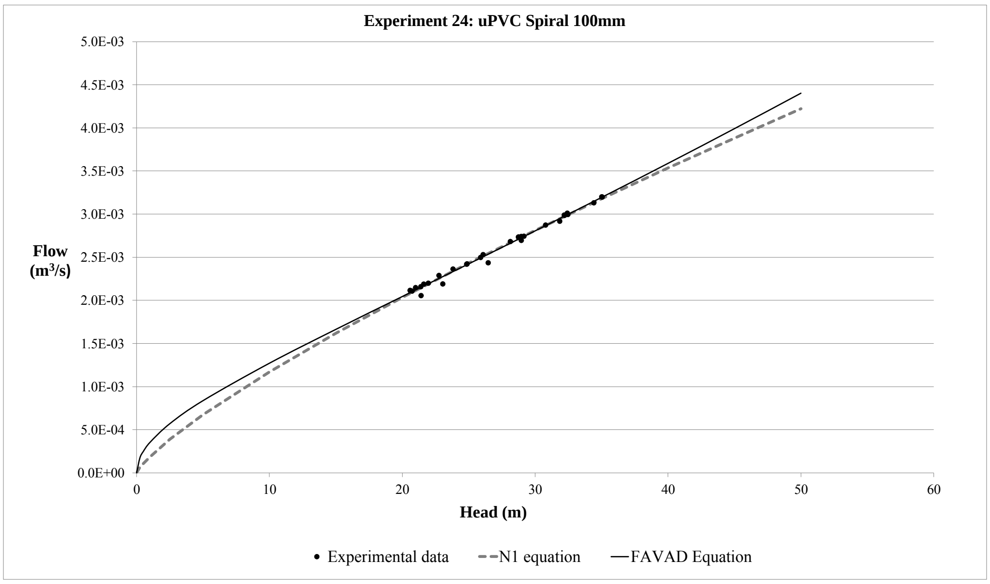




Experiment 24: uPVC Spiral 100mm

EXPERIMENTAL PARAMETERS	
1 Bar =	10.1937 m
1 l/s =	0.0010 m^3/s
g =	9.81 m/s^2
A_0 =	1.000E-04 m^2
N1 PARAMETERS	
C =	1.871E-04
N1 =	0.7967
R^2 =	0.99041
SSE =	4.194E-04
FAVAD PARAMETERS	
C_dA_0 =	7.836E-05 m^2
C_d =	0.7836
m =	1.587E-06
R^2 =	0.99092
SSE =	4.195E-04

Sample	Flow (l/s)	Pressure (bar)	Flow (m^3/s)	Pressure head (m)	C_dA (m^2)	A (m^2)	N_1 Flow (m^3/s)	FAVAD Flow (m^3/s)
1	2.0548	2.1007	2.0548E-03	21.4138	1.0025E-04	1.2793E-04	2.1485E-03	2.1521E-03
2	2.1901	2.2607	2.1901E-03	23.0447	1.0300E-04	1.3144E-04	2.2779E-03	2.2756E-03
3	2.4352	2.5959	2.4352E-03	26.4614	1.0688E-04	1.3639E-04	2.5432E-03	2.5353E-03
4	2.6952	2.8407	2.6952E-03	28.9571	1.1308E-04	1.4429E-04	2.7325E-03	2.7262E-03
5	2.9176	3.1241	2.9176E-03	31.8465	1.1672E-04	1.4895E-04	2.9476E-03	2.9487E-03
6	3.1308	3.3759	3.1308E-03	34.4125	1.2049E-04	1.5375E-04	3.1353E-03	3.1482E-03
7	2.8726	3.0200	2.8726E-03	30.7849	1.1688E-04	1.4915E-04	2.8690E-03	2.8667E-03
8	2.6819	2.7593	2.6819E-03	28.1275	1.1416E-04	1.4568E-04	2.6699E-03	2.6626E-03
9	2.4190	2.4372	2.4190E-03	24.8445	1.0957E-04	1.3982E-04	2.4186E-03	2.4122E-03
10	2.1584	2.0987	2.1584E-03	21.3931	1.0535E-04	1.3444E-04	2.1469E-03	2.1505E-03
11	2.1074	2.0340	2.1074E-03	20.7339	1.0449E-04	1.3333E-04	2.0940E-03	2.1006E-03
12	2.1986	2.1538	2.1986E-03	21.9551	1.0593E-04	1.3518E-04	2.1917E-03	2.1931E-03
13	2.4974	2.5400	2.4974E-03	25.8919	1.1080E-04	1.4140E-04	2.4995E-03	2.4919E-03
14	2.7440	2.8600	2.7440E-03	29.1539	1.1473E-04	1.4641E-04	2.7473E-03	2.7413E-03
15	2.9955	3.1841	2.9955E-03	32.4581	1.1870E-04	1.5147E-04	2.9926E-03	2.9961E-03
16	3.1985	3.4379	3.1985E-03	35.0452	1.2198E-04	1.5566E-04	3.1812E-03	3.1976E-03
17	3.0108	3.1800	3.0108E-03	32.4159	1.1939E-04	1.5235E-04	2.9895E-03	2.9928E-03
18	2.7340	2.8200	2.7340E-03	28.7462	1.1512E-04	1.4690E-04	2.7166E-03	2.7100E-03
19	2.3632	2.3366	2.3632E-03	23.8181	1.0932E-04	1.3950E-04	2.3386E-03	2.3343E-03
20	2.1476	2.0600	2.1476E-03	20.9990	1.0580E-04	1.3502E-04	2.1153E-03	2.1207E-03
21	2.1111	2.0213	2.1111E-03	20.6048	1.0500E-04	1.3399E-04	2.0836E-03	2.0908E-03
22	2.1881	2.1200	2.1881E-03	21.6106	1.0626E-04	1.3560E-04	2.1642E-03	2.1670E-03
23	2.4226	2.4400	2.4226E-03	24.8726	1.0967E-04	1.3994E-04	2.4207E-03	2.4144E-03
24	2.7410	2.8400	2.7410E-03	28.9501	1.1501E-04	1.4676E-04	2.7320E-03	2.7256E-03
25	2.9853	3.1600	2.9853E-03	32.2120	1.1875E-04	1.5154E-04	2.9745E-03	2.9771E-03
26	3.2001	3.4345	3.2001E-03	35.0100	1.2210E-04	1.5581E-04	3.1786E-03	3.1948E-03
27	2.9888	3.1572	2.9888E-03	32.1839	1.1894E-04	1.5178E-04	2.9725E-03	2.9749E-03
28	2.7338	2.8193	2.7338E-03	28.7391	1.1513E-04	1.4691E-04	2.7161E-03	2.7094E-03
29	2.5305	2.5586	2.5305E-03	26.0818	1.1186E-04	1.4275E-04	2.5140E-03	2.5064E-03
30	2.2892	2.2324	2.2892E-03	22.7565	1.0834E-04	1.3825E-04	2.2552E-03	2.2538E-03
31	2.1165	2.0193	2.1165E-03	20.5842	1.0532E-04	1.3439E-04	2.0819E-03	2.0892E-03



Experiment 24: uPVC Spiral 100mm